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THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

EDITED BY

GEORGE E. HALE
Mount Wilson Solar Observatory of the Carnegie Institution of Washington

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JUNE 1919

ON THE USE OF GRATING SPECTRA FOR DETERMINING SPECTRAL TYPE AND ABSOLUTE MAGNITUDE OF THE STARS . . . . . *Bertil Lindblad* 289

COLOR-SENSITIVENESS OF PHOTO-ELECTRIC CELLS . . . . . *T. Shinomiya* 303

STUDIES BASED ON THE COLORS AND MAGNITUDES IN STELLAR CLUSTERS. XII *Harlow Shapley* 311

THE HELIUM SPECTRUM AND THE UNIT ELECTRICAL CHARGE . . . . . *Fernando Sanford* 337

PHOTO-ELECTRIC MEASURES OF THE LIGHT OF NOVA AQUILAE NO. 3 *Joel Stebbins and Elmer Dershem* 344

REVIEWS:

A Treatise on the Sun's Radiation and Other Solar Phenomena, FRANK H. BIGELOW (H. Bateman), 355; *Mirrors, Prisms and Lenses, a Text-book of Geometrical Optics*, JAMES P. C. SOUTHALL (C. S. Hastings), 359.

A CORRECTION . . . . . *E. E. Barnard* 360

INDEX 361

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ON THE USE OF GRATING SPECTRA FOR DETERMINING SPECTRAL TYPE AND ABSOLUTE MAGNITUDE OF THE STARS

By BERTIL LINDBLAD

PRELIMINARY NOTICE

In a recent paper[1] I have tried to give an exposition of the method of deriving the photographic effective wave-lengths in grating spectra, especially used by Hertzsprung[2] and by Bergstrand[3] for the determination of the color and spectral type of the fixed stars. The instrument employed was the twin 6-inch astrograph at the Upsala Observatory with Zeiss triplet lenses (aperture 15 cm, focal length 150 cm). The constant of the wire grating in front of one of the objectives was 1.3422 mm. This instrument had previously been used for determining effective wave-lengths by

[1] *Arkiv för Matematik, Astronomi och Fysik utgifvet af K. Svenska Vetenskaps akadamien*, 13, No. 26, 1918.

[2] *Bulletin astronomique*, 25, 5, 1908; *Publ. des Astrophysikalischen Observatoriums zu Potsdam*, 22, No. 1, 1911; *Astrophysical Journal*, 42, 92, 1915; *Contributions from Mount Wilson Solar Observatory*, Nos. 100 and 101.

[3] *Astronomische Nachrichten*, 177, 241, 1908; *Nova Acta R.S. Scient. Upsal.*, Serien IV, 2, No. 4, 1909, also in *Comptes Rendus*, 148, 1079, 1909.

Bergstrand and Lindblad[1] for fixed stars, and by Lundmark and Lindblad[2] for some spiral nebulae and globular clusters.

One of the chief results of the investigation was that the effective wave-length λ_e showed a very close relation to the spectral type defined in the Harvard system. On the whole the effective wave-length seemed to be perfectly analogous to the color-index. The difference in λ_e between classes B and K amounts to about 22 $\mu\mu$, the mean error for a single measured image being ± 2 $\mu\mu$. But it was also evident that for the later spectral types the color was closely related to the absolute magnitude of the star, a fact which previously has been more or less clearly expressed by Kapteyn, Van Rhijn, Adams, and Monk.[3] The spectral type being the same, a star will be redder the smaller its absolute magnitude, i.e., the greater its luminosity. From the colors of Osthoff[4] and the list of parallaxes prepared by Walkey[5] I found for the coefficient $\gamma = \frac{\Delta C}{\Delta M}$, where C and M denote color and absolute magnitude, the value $-0^{c}.12$, corresponding to $-0^{M}.053$ in color-index. From the effective wave-lengths for 26 stars in the catalogue of 500 parallaxes given by Adams and Joy[6] I found $\gamma = -0.93$ $\mu\mu$ for the types Go to K5, corresponding to $\gamma = -0^{M}.052$ in color-index. The effect is so great that it seems quite possible to compute the absolute magnitude by independent determinations of color and spectral type. The effective wave-lengths for the stars from the list of Adams and Joy could be arranged in two distinct series, one representing the giants, the other the dwarfs. Thus it seems as if we had here a valuable complement to the method of Adams and Joy for the determination of absolute magnitudes.

Now the question arises, What may be the cause of this relation between color and absolute magnitude? It seems most reasonable

[1] *Arkiv för Mat., Astr., och Fysik*, **11**, No. 17, 1916.

[2] *Astrophysical Journal*, **46**, 206, 1917; *Astronomische Nachrichten*, **205**, 161, 1917.

[3] *Astrophysical Journal*, **44**, 45, 1916; *Mt. Wilson Contr.* No. 119, 1916. See also a recent paper of Seares, *Publications of the Astronomical Society of the Pacific*, **30**, 122, 1918.

[4] *Astronomische Nachrichten*, **153**, 141, 1900.

[5] *Journal of the British Astronomical Association*, Appendix to **27**, 1917.

[6] *Astrophysical Journal*, **46**, 313, 1917; *Mt. Wilson Contr.* No. 142, 1917.

to assume that we have here to deal with an effect of a selective absorption, more pronounced for the shorter wave-lengths, in the vast atmospheres of the immense stars which have been characterized as giants. The spectral lines which define the spectral type, for instance in the Harvard system, are dependent on the temperature and composition of the photospheric layers of the star; the color, at least for the later spectral types, in addition depends on the dimensions of the overlying atmosphere. Thus the photospherical conditions and the dimensions of a star seem to be uniquely determined by the spectral lines and the color in combination.

But have we really exhausted all the possibilities of the grating spectra by measuring the effective wave-length that is the center of the density in the photographic image of the spectrum? There is at least another quantity that may be measured as well, and that is the length of the spectrum. In the investigation mentioned above I have measured the length of the spectra for some stars of different spectral types.[1] Thereby it was found that the outer limit of the spectra was tolerably constant, but that the inner limit varied rather strongly. Thus the spectra were much shorter for stars of the later types than for those of the earlier. But since the outer limit only varies slightly, and besides is often hard to define, it is of no use to measure it, and in this way we have only the inner limit left. This inner limit defines the shortest wave-length in the spectrum of a star that has had any effect on the photographic plate during a particular exposure. In the following I will call this wave-length simply the minimum wave-length, λ_{min}. For good images of grating spectra taken with the astrograph of the observatory of Upsala this minimum wave-length is rather sharply defined and easy to measure. It is determined in a manner analogous to that used for the effective wave-length. The distance between the inner limits of the two spectra, s_{min}, is measured with the micrometer of the measuring machine. Then for the center of the plate we have, if f is the focal length, c the grating constant:

$$\lambda_{min} = \frac{c}{2f} s_{min}$$

[1] *Loc. cit.*, p. 6.

One of the greatest merits of the grating spectra is that there are good controls on the quality of the images. The chief control is the symmetry of the two spectra, not only the symmetry of the outlines, but also of the distribution of intensity within the two images. A second control is the regularity of the central image. As a third control one has the intensity and sharpness of the blackening of all the three images.

Naturally the minimum wave-length as well as the effective wave-length depends on the instrumental conditions, the telescope employed, the grating constant, and the properties of the plates. The sharp limit is produced by several causes beside the character of the energy-curve of the spectrum, as the sensibility-curve of the plates, the absorption in the lenses, and the secondary spectrum of the objective, i.e., the variation of the focal length with the wave-length. The limit is broad and well defined for the white stars; when λ_{min} increases for the redder stars the limit is drawn to a point, and for extremely red stars, the giants of type M, it is rather diffuse.

The minimum wave-length is dependent on the intensity of image, and must be defined for a certain intensity. As parameter of correction I have chosen the same as for the effective wave-length, the diameter D of the central image. The normal intensity is also the same, $D = 0.14$ revolutions of the micrometer, corresponding to 0.07 mm. The correction seems at first to diminish for the redder stars; it is greater for λ_{min} than for λ_c, but is well defined and lies within reasonable limits.

Thus we have found in the minimum wave-length a new and easily measurable color-equivalent, determined from the shortest possible wave-lengths in the spectrum. The question now is what we may gain by this new color-equivalent. In the foregoing we have seen that the later spectral types do not uniquely determine the color of a star, this being moreover in a certain degree dependent on the absolute magnitude. In order to simplify the reasoning we may say that there are two different series of stars, giants and dwarfs, corresponding to two distinct series of color. In each of these series taken alone the spectral type and the color advance with falling temperature; in the investigation previously mentioned

it was found that for the stars of Wilsing and Scheiner,[1] in all probability mostly giants, the relation between temperature and effective wave-length could be represented by the equation:

$$\lambda_e = 403.4\,\mu\mu + 11.4 \cdot \frac{10^4}{t}.$$

According to the law of Wien this means that there is a linear relation between λ_e and the wave-length for the maximum of energy in the spectrum. The difference between the two series is probably caused by a different absorption in the stellar atmospheres. As a type for these atmospheres we may take that of the sun. From the observations of Vogel the coefficient of transmission for different wave-lengths has been determined by Seeliger.[2] From these values of the coefficient of transmission I have computed in Table I the coefficient of absorption n, defined in the equation:

$$I = I_o e^{-ns},$$

where I is the intensity of light for a certain wave-length, s the number of solar atmospheres which correspond to the distance covered in the absorbing medium.

The law of Planck for the intensity of radiation of a black body may be written for short wave-lengths and not too high temperatures:

$$I = C\lambda^{-5} e^{-\frac{c}{\lambda t}}.$$

If the beam of light also has to travel through an absorbing medium, we have

$$I = C\lambda^{-5} e^{-\frac{c}{\lambda t}} \cdot\ e^{-ns}.$$

If n were proportional to $1/\lambda$, the effects of temperature and absorption would be of the same quality, and would produce analogous changes in the intensity distribution of the spectrum. Then theoretically we could gain nothing by the introduction of a new color-equivalent such as the minimum wave-length, for then it would be impossible to separate the effects of the two variables—temperature and absorption—even if the new color-equivalent

[1] *Publ. des Astrophysikalischen Observatoriums zu Potsdam*, **19**, 1909.

[2] *Sitzungsber. der K. Bayer. Akad. der Wiss. Math. Phys. Kl.*, **21**, 247–72,, 1891.

were determined from another part of the spectrum, for instance as here from the shortest possible wave-lengths. Now according to Müller,[1] Abney, and Langley the coefficient of absorption for the atmosphere of the earth increases with a much greater speed than the function C/λ. According to Table I it seems as if the same

TABLE I

Wave-length	Coefficient of Transmission	n	$\frac{C}{\lambda}$
662 $\mu\mu$	0.77	0.26	0.32
579	0.66	0.42	0.37
513	0.63	0.46	0.41
470	0.64	0.45	0.45
443	0.57	0.56	0.48
409	0.54	0.62	0.52

were in some degree true for the atmosphere of the sun, at least for the photographic part of the spectrum. In the last column C/λ is made equal to n for $\lambda = 470\ \mu\mu$, which is very near the outer limit of the grating spectra. At all events we have some reasons to believe that λ_{min} may be considered as an *absorption-equivalent;* it is a priori probable that λ_{min} is more sensible for absorption than λ_c, which on the whole principally has the character of a temperature-equivalent.

But before we go further in the theoretical discussion I will refer to the results obtained in a preliminary investigation of the subject. For a sequence of thirty-five stars, chosen to represent different spectral types and absolute magnitudes, I have determined λ_c and λ_{min}. Twenty-five of the stars were taken from the catalogue of Adams and Joy, and as a complement five stars of earlier types were measured. In addition four stars of *c*-character in Miss Maury's classification have been included. According to Hertzsprung[2] the stars of this character are of a very high luminosity; from the catalogue of Adams and Joy it is seen that their absolute magnitudes are on an average smaller than those of the other giant stars. To the *c*-stars I have added δ Cephei; though only being of

[1] *Photometrie der Gestirne*, p. 139.

[2] *Zeitschrift für wissenschaftliche Photographie*, 3, 429; 5, 86.

ac-character in Miss Maury's classification, there cannot be any doubt about its exceedingly great luminosity; its absolute magnitude (apparent magnitude in the distance 10 parsecs) may be estimated to $-2^{M}.1$

The telescope and grating were those mentioned above, the plates were Imperial S.S., Emulsion 9629A. These plates seem to be less rapid than those employed in the foregoing investigation of the emulsion 9220A. As developer Rodinal was used. A good control on the quality and development of the plates would be to take some control stars on each plate, but this would involve a considerable increase of labor. In this case I have generally taken many stars of different kinds on the same plate. A systematic difference between the different plates has not been discovered. The distribution of the stars between the plates is shown in Table II. The numbers refer to the first column of Table IV.

TABLE II

Plate Number	Date 1918	Stars
1	Sept. 14	2, 5, 6, 7, 8, 17, 18, 22, 29, 34
2	Sept. 20	32
3	Sept. 21	26, 27, 28, 35
4	Sept. 21	15, 30, 31, 33
5	Sept. 24	10, 11, 12
6	Sept. 26	13, 14, 16, 19, 24, 25
7	Sept. 27	3, 4, 9, 19, 20, 21, 23
8	Oct. 4	1

The effective wave-lengths were determined in the usual way. After a plate was measured in one position it was turned 180° and measured again. The correction for the intensity of image, measured by the diameter D of the central image, was taken from the investigation previously referred to, but for safety the limits were taken more close to the normal diameter. The correction for the zenith-distance was also taken from the paper mentioned.

The minimum wave-length was measured according to the principles mentioned above. As far as possible the measurements were performed without knowledge of either the spectral type or

[1] Hertzsprung, *Astronomische Nachrichten*, **196**, 201, 1914.

the luminosity of the star in question. The distance between the inner limits of the two spectra was measured with a double thread of the microscope of the measuring-machine, and in both positions of the plate. A rigorous control was applied to the quality of the images, of which only the best ones were measured.

Table III shows the correction of λ_{min} for the intensity of image. I have found three distinct types for the effect in question, corresponding to three different groups of stars. The first group contains all stars with $\lambda_{min} < 378\ \mu\mu$; the second consists of the dwarfs

TABLE III

(Unit of D=0.01 of a rev. of the micrometer)

Diameter	12	13	14	15	16
Group I	−4.6 μμ	−2.1 μμ	0.0 μμ	+2.1 μμ	+4.4 μμ
Group II	−2.9	−1.4	0.0	+2.2	+5.0
Group III	−1.2	−0.2	0.0	0.0	0.0

with $\lambda_{min} > 378\ \mu\mu$; the third is formed by the giants from the catalogue of Adams and Joy with $\lambda_{min} > 378\ \mu\mu$. Obviously the magnitude of the correction diminishes with increasing redness of a star. In consequence of this it is probable that the effect, at least for the first group, is principally produced by the same cause as the usual widening of stellar disks with increasing time of exposure, for otherwise we should have to expect a less marked effect for the white stars than for the redder. The choice of the diameter D of the central image as parameter of correction, which might be open to some objections, thus seems more legitimate.

For exceedingly red stars, $\lambda_c > 435\ \mu\mu$, the magnitude of the effect increases considerably; in this way we have a fourth type of the effect, which is here conditioned by the less rapid fall of the spectral intensity on the side of the shorter wave-lengths. This type of the effect seems also to hold true for the c-stars of the later types. The correction used for the stars in question is: $\Delta\lambda = 3.5\ \mu\mu\ (D-14)$, where D is expressed in hundredths of a revolution of the micrometer.

Then in order to derive the definitive values of λ_{min}, when they are greater than $378\ \mu\mu$, we must know something about the

absolute magnitudes of the stars. As shall be mentioned in the following, this will be possible by a combination of λ_c with a preliminary value of λ_{min}. On the other hand the appearance of the effect for a certain star may give some information about its luminosity.

TABLE IV

No.	Star	App. Mag.	R.A. 1900	Decl. 1900	Spectrum	Abs. Mag.	λ_c	λ_{min}	n
							$\mu\mu$	$\mu\mu$	
1 ..	τ Cygni	3.8	$21^h 10^m 8$	37° 37′	F1	+1.9	419.3	375.4	3
2 ..	σ Pegasi	5.3	22 47.3	9 18	F4	+3.9	419.4	374.0	1
3 ..	Boss 5772	6.1	22 18.8	20 21	F5	+4.5	419.9	375.5	2
4 ..	Groom.3357	6.6	20 56.1	39 51	F7	+4.6	422.3	373.4	2
5 ..	Boss 5920	6.5	22 53.5	8 50	G0	+4.4	420.6	374.5	1
6 ..	Lal. 47207	6.2	23 59.6	34 6	G0	+4.4	422.5	375.0	1
7 ..	85 Pegasi	5.9	23 56.9	26 33	G1	+5.8	419.2	375.3	1
8 ..	η Pegasi	3.1	22 38.3	29 42	G2	+1.2	425.4	379.9	2
9 ..	ϵ Androm.	4.5	0 33.3	28 46	G3	+1.3	423.1	379.2	4
10 ..	Fed. 4371	7.5	23 1.2	67 52	G5	+7.0	421.2	376.0	2
11 ..	η Piscium	3.7	1 26.1	14 50	G5	+0.3	426.5	385.2	1
12 ..	Boss 6097	6.6	23 39.9	55 15	G6	+0.7	425.8	383.5	1
13 ..	24 Vulpec.	5.4	20 12.5	24 22	G7	+0.7	429.1	386.8	2
14 ..	ϵ Cygni	2.6	20 42.2	33 36	G8	+0.8	428.4	386.5	2
15 ..	η Cephei	3.6	20 43.3	61 27	G9	+2.4	429.6	380.3	2
16 ..	Lal. 39704	7.0	20 29.3	41 33	K0	+6.4	428.6	380.5	1
17 ..	Pi 22^h 214	6.5	22 40.9	29 55	K0	+4.4	425.9	382.3	2
18 ..	ι Cephei	3.7	22 46.1	65 40	K0	+1.1	427.7	383.5	3
19 ..	ϵ Pegasi	2.5	21 39.3	9 25	K0	−0.3	435.7	385.6	3
20 ..	Lal. 38683	7.3	20 6.6	15 53	K1	+6.7	432.3	379.7	1
21 ..	Boss 5602	6.5	21 41.8	25 6	K3	+1.5	436.2	384.2	1
22 ..	Boss 5868	6.1	22 39.6	38 56	K4	+0.9	438.8	386.6	1
23 ..	Boss 5976	5.6	23 8.5	56 37	K5	+6.6	429.7	381.2	4
24 ..	61^1 Cygni	5.6	21 2.4	38 15	K7	+7.9	430.4	382.8	2
25 ..	61^2 Cygni	6.3	21 2.4	38 15	K8	+8.7	430.5	379.9	1
26 ..	β Cephei	3.3	21 27.4	70 7	B1; IIIa	.....	411.1	373.0	4
27 ..	o Herculis	3.8	18 3.6	28 45	A; VIIb	.....	415.7	371.4	2
28 ..	δ Cygni	3.0	19 41.9	44 53	A; VIIb	.....	414.8	374.7	3
29 ..	α Pegasi	2.6	22 59.8	14 40	A; VIIIb	+0.35	412.6	374.0	2
30 ..	ϵ Cephei	4.2	22 11.3	56 33	A5; Xa, b	+3.80	418.0	374.5	1
31 ..	4 Lacertae	4.6	22 20.4	48 58	B9; VIc	.....	414.9	376.0	3
32 ..	α Cygni	1.3	20 38.0	44 56	A2p; VIIIc	.....	413.2	376.4	1
33 ..	d Draco.	5.0	18 30.9	56 58	F8p; XIIIc	.....	423.8	380.7	2
34 ..	ρ Cass.	5.0	23 49.4	56 57	G4p; XIIIc	−0.4	428.7	383.5	1
35 ..	δ Cephei	var.	22 25.4	57 54	G0; XIVac	.....	423.9	378.7	2

As the material is too scanty for an accurate determination of the effect, I have not generally used corrections exceeding 5 $\mu\mu$.

For the influence of the zenith-distance I have assumed the same values of the correction as for the effective wave-length. It is evident that λ_{min} is much less sensible for changes in the spectral

intensity for stars of the earliest spectral types, and therefore I have not applied the correction for stars with λ_{min} less than 375 $\mu\mu$. It may be that the correction for the zenith-distance ought to be a little greater than I have assumed here, but in most cases it is too small to be of any importance.

Table IV contains the results of the measurements. The first column contains the number of the star, the second to fifth the

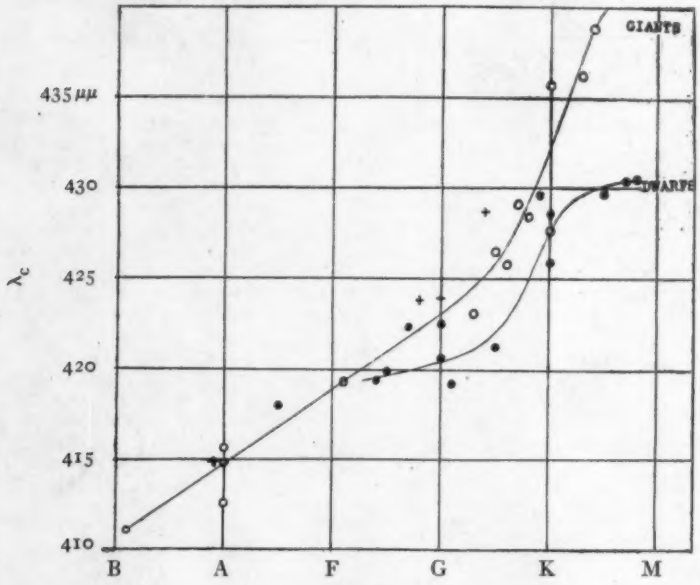

FIG. 1

name of the star, its visual magnitude, R.A., and Decl. The sixth and seventh contain the spectral type and absolute magnitude according to Adams and Joy (spectrum estimated). For the last ten stars the spectral type is due to Harvard; for α Pegasi and ϵ Cephei the absolute magnitudes are computed from the parallax-list prepared by Walkey. The last columns contain the effective and minimum wave-lengths and the number of images from which λ_{min} has been derived. In computing definitive values of λ_{min} the images with $D < 12$ are generally excluded.

Fig. 1 shows the relation between the effective wave-length λ_c and the spectral type. The open circles indicate giants, the black

circles dwarfs, the circles with a cross represent an intermediate type. The five *c*-stars are represented by crosses; as mentioned above, they may be considered as the most pronounced giants. The early-type stars with character *a* and *b* are designated as giants, except ϵ Cephei.

The character of the diagram is precisely the same as had been found in the previous paper.[1] Five stars of the giant series are common for the two investigations. From these stars it is seen

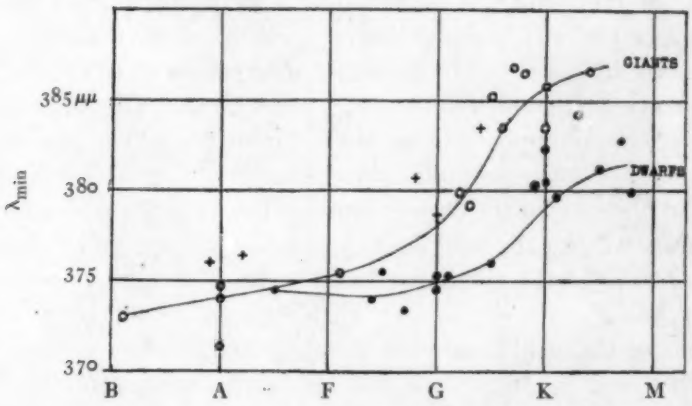

FIG. 2

that the effective wave-lengths for the Imperial plates of the emulsion 9629A are on an average 3.0 $\mu\mu$ smaller than those measured on plates of the emulsion 9220A. This correction seems to hold unchanged through the whole spectral series. For the coefficient

$$\gamma_c = \frac{\Delta\lambda_c}{\Delta M},$$

where M is the absolute magnitude, I find the value -0.87 $\mu\mu$ from the stars of the spectral types Go to K8. In the previous paper I found $\gamma_c = -0.93$ $\mu\mu$ for the types Go–K5.

In Fig. 2 the relation between the minimum wave-length λ_{min} and the spectral type is shown. It is at once evident that the difference between giants and dwarfs is far more marked than for λ_c.

$$\gamma_{min} = \frac{\Delta\lambda_{min}}{\Delta M}$$

[1] *Loc. cit.*, pp. 45 f., 73.

is found to be $-1.10\ \mu\mu$ for the types Go to K8, mean type G9. Thus the coefficient γ has a somewhat higher value than for λ_c, though the differences in λ_{min} between different spectral types are generally less than the corresponding differences in λ_c. It is evident that λ_{min} has a lower limit at about $373\ \mu\mu$, which seems to be reached already by some dwarfs of types F–G. This limit is caused by the fact that the maximum of energy in the spectrum begins to fall in too short wave-lengths, outside the limit of the sensibility of the plate. It is moreover very probable that the appearance of Fig. 2 is in a high degree conditioned by the instrumental means, for instance the secondary spectrum of the objective. A consequence of the lower limit of λ_{min} must be that for the early types the effect of different luminosity is diminished. That nevertheless there are some possibilities for a successful application of the method, at least for the greater luminosities, is indicated by the high values of λ_{min} for the two *c*-stars 4 Lacertae and α Cygni. The mean error of λ_{min} for a single measured image I have found to be about $\pm 1.3\ \mu\mu$.

Fig. 1 and Fig. 2 illustrate the relations and fundamental differences between the three spectral symbols, the spectral type determined from the lines in the spectrum, and the color-equivalents λ_c and λ_{min}. The spectral lines define the photospheric conditions of a star; then according to Fig. 2 the minimum wave-length seems to determine the absolute magnitude with a fair degree of accuracy. For the real color-equivalent λ_c the effects of absorption are on the whole of a subordinate importance. This leads us to the important conclusion that the effective wave-length λ_c may be used as a substitute for the spectral class in the determination of absolute magnitude by means of λ_{min}. The relation between λ_c and λ_{min} is shown in Fig. 3. The differences between giants and dwarfs are still well marked. Thus when the absolute magnitude is known from a combination of λ_{min} and λ_c in the way indicated by Fig. 3, then λ_c may be used to determine the exact spectral type by means of Fig. 1. In this way we should have determined both spectral type and absolute magnitude with quantities measured directly on the grating spectra *and without any reference to the spectral lines.*

If this principle can be realized in practice with the necessary accuracy also for relatively long exposures, it would be of great importance, because the grating spectra can be photographed with relatively small instruments for stars of very faint magnitudes, for which the spectral lines cannot be determined even with the largest instruments. At any rate Fig. 2 represents a method for deriving absolute magnitudes of later-type stars which promises to be very convenient in practice, and seems to be a valuable complement to the method of Adams and Joy.

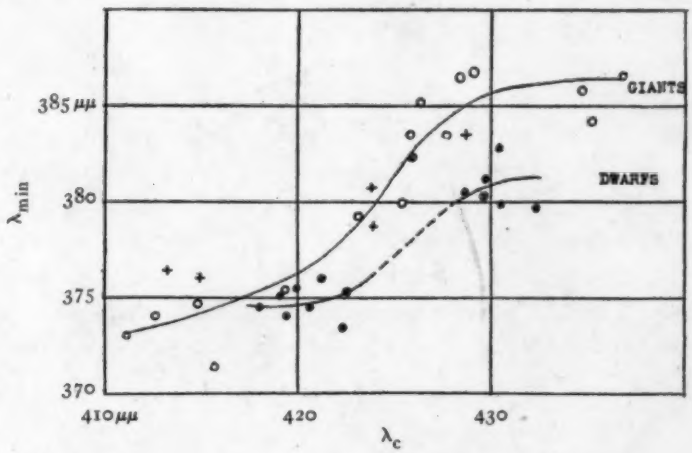

FIG. 3

There is, however, another important conclusion to be drawn from Figs. 1 and 3. Hertzsprung[1] has found that the effective wave-lengths of absolutely faint stars have a superior limit, which seems to be reached at the absolute magnitude +8 (app. mag. in the distance 10 parsecs). Now the two stars in the system of 61 Cygni, of the spectral types K7 and K8, are of the absolute magnitudes 7.9 and 8.7; their effective wave-lengths have been found to be 430.4 $\mu\mu$ and 430.5 $\mu\mu$. If the division of the stars in giants and dwarfs, as it is shown in the catalogue of Adams and Joy, holds through the whole stellar system, then from the dwarf series in

[1] *Astrophysical Journal*, 42, 111, 1915; *Mt. Wilson Contr.* No. 101.

Fig. 1 and 3 we may conclude in accordance with the facts mentioned *that stars with* $\lambda_c > 433\ \mu\mu$ *are all giants.* $\lambda_c = 433\ \mu\mu$ corresponds to about $+1.2$ in color-index.

Further investigations on the subject will be continued at the observatory of Upsala.

ASTRONOMICAL OBSERVATORY, UPSALA
December 2, 1918

COLOR-SENSITIVENESS OF PHOTO-ELECTRIC CELLS

By T. SHINOMIYA

In various photometric measurements the photo-electric cell proves to be a simple, reliable, and accurate instrument. It has been shown in a previous paper by J. Kunz that cells can be constructed in which for a constant potential-difference the photo-electric current is proportional to the intensity of light over a wide interval of illumination. P. Guthnick and R. Prager,[1] Elster and Geitel, Pohl and Pringsheim, have already studied the color-sensitiveness of photo-electric cells throughout the spectrum. The curves given by Guthnick and Prager contain, however, only a few points, which hardly suffice to determine the maximum sensitiveness and the nature of the curve with much accuracy. Moreover, the question arises as to how the colloidal modification of the alkali hydrides affects the color-sensitiveness. The following report contains the first measurements made in the Physical Laboratory of the University of Illinois. In Table I the dimensions of the cells

TABLE I

K	Diameter of Bulbs	Diameter of Anode Rings
K	4.2 cm	2.2 cm
K-H No. 1	5.7	3.3
K-H No. 2	5.0	2.3
K-H No. 3	6.0	2.7
Na	4.1	2.2
Na-H	4.1	2.2
Rb	4.1	2.2
Rb-H	4.1	2.2
K-H Pyrex glass	3.1	1.3

are given. The anode rings had a cross of very fine platinum wire, so as to make the electrostatic field between the sensitive alkali surface and the anode as uniform as possible. The beam of light was allowed to enter the photo-electric cell through a narrow

[1] *Veröffentlichungen der Sternwarte zu Berlin-Babelsberg*, 1, 1, 1914.

opening, the rest of the inner surface of the bulb being coated with alkali metal.

The source of light was a 15-ampere nitrogen-filled tungsten lamp made by the General Electric Company. The light was condensed on a slit of width 0.7 mm by a system of condensing lenses. By another lens the image of the slit was thrown on a screen and a prism placed in this beam of light. The position of minimum deviation was chosen for the green-blue light. A pretty pure spectrum was obtained, and all reflected and stray light was eliminated by five diaphragms placed in suitable positions. The whole optical system was contained in a box of thin board blackened inside. A table, carrying a slit S, the thermo-couple, and the box with the photo-electric cell could be moved by means of a fine screw along a scale M rigidly attached to a pier. In this way the slit was brought to any desired position of the spectrum and allowed the monochromatic beam of light to fall either on the thermo-couple or on the photo-electric cell. The scale was read outside the closed frame.

The scale M was calibrated in terms of wave-length by a Hilger spectrometer. The incident light was not absolutely monochromatic. A mean wave-length was used. As the sensitiveness of the photo-electric cell changes in a continuous way through the spectrum, this small deviation from the ideal condition has little effect on the final curve.

The energy of the light passing through the slit S was measured by means of a thermo-couple furnished by W. W. Coblentz from the Bureau of Standards. The slit of the thermopile was a little narrower than the slit S, so that the former was always covered by light. The thermo-electric current was measured with a high-sensitive moving-coil galvanometer (figure of merit $2.7 \cdot 10^{-9}$). The galvanometer and the wires connecting it with the thermo-couple were completely covered with thick boards of wood in order to keep the temperature constant and to prevent air currents. The galvanometer deflections were quite steady and could be repeated with ease.

The thermo-couple was calibrated by means of the light from a Hefner lamp. The lamp was placed at a distance of 50.1 cm from

the slit. The corresponding deflection was 154.6 mm. The energy radiated from a Hefner lamp[1] was taken as 8.3 ergs per second per square centimeter at a distance of 1 meter. At 50.1 cm it is about 33 ergs. This flow of energy produced a deflection of 154.6 mm. Therefore the deflection of 1 mm corresponds to the flow of energy of 0.214 ergs per second per square centimeter. The area of the slit S admitting the light to the photo-electric cell was 0.272 cm and the energy passing through that slit per 1 mm deflection of the thermo-couple galvanometer was $0.214 \cdot 0.272 = 0.0581$ ergs.

The galvanometer, which measured the photo-current, had 480 ohms internal resistance, a critical damping resistance of 9600 ohms, and a sensitiveness of $4 . 10^{-10}$ amperes for a scale distance of 1.25 meters. To safeguard against short circuit a resistance of 100,000 ohms was inserted in the photo-electric circuit. A shutter in front of the photo-electric cell was opened and closed by the observer at his observing position by means of pulleys and strings.

At first the characteristic curve of each cell was determined. The source of light was of course kept as constant as possible. A small deviation from the constant 15 amperes made itself felt readily in the galvanometer deflection. These deflections were, however, quite steady and could easily be repeated as long as the source of light was constant.

The characteristic curves are shown in Fig. 1, in which the abscissae represent voltages, the ordinates currents. K-H No. 1 and Rb-H appear more sensitive than the alkali metals K and Rb respectively; on the other hand, Na-H and K-H No. 2 and K-H No. 3 are less sensitive for higher voltages than the pure metals. All cells of course contained argon. K-H No. 3 was the cell which J. Stebbins and J. Kunz used in the photometry of the corona at the solar eclipse of June 8, 1918.

The characteristic curve having been determined, a constant potential-difference was chosen lying on the horizontal branch of that curve. This potential-difference and the heating current of the source of light were kept very constant during the time in which the final readings for the sensitiveness of a given cell through

[1] E. L. Nichols, *Physical Review*, **21**, 169, 1905.

the spectrum were taken. The photo-electric cell with the slit was moved first in one direction, then in the opposite direction, through the spectrum. For the same position the deflection of the galvanometer was the same.

A photo-electric cell of a pyrex glass tube was constructed. The deflections even for a small potential-difference were very variable,

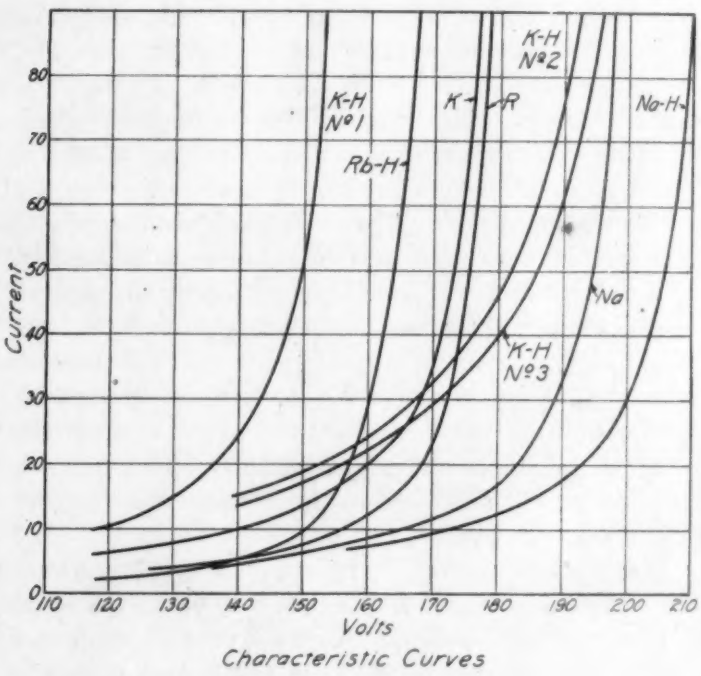

FIG. 1

and it was impossible to get a curve for its sensitiveness. The other cells, however, were constant. Only when the potential-difference approached the critical value did the deflections become a little unstable.

Table II contains the readings of the scale M, the wave-length in angstroms, the deflections of the galvanometer measuring the energy of the beam of light, and the photo-electric currents as galvanometer deflections. The numbers below the alkali indicate

the potential-difference applied to the cell when the readings were taken. A deflection of 102 mm of the photo-electric galvanometer means a current of $102.4 \cdot 10^{-10} = 4.08 \cdot 10^{-8}$ amperes. The corresponding deflection in the thermo-couple circuit was 6.8 mm, i.e.,

TABLE II

Scale	Wave-Length	Deflection of Light Energy	K-H No. 1 129	K-H No. 2 153	K-H No. 3 160	K 149	Na 142	Na-H 165	Rb 140	Rb-H 118
40...	6800	104.0	2.5	2.5	3.1	2.9	1.9	1.5	0.8	0.7
45...	6427	76.0	3.0	3.1	3.5	3.2	2.1	1.8	1.0	0.9
50...	6092	57.0	4.1	4.2	4.4	5.0	2.6	2.1	1.4	1.0
52...	5950	50.8	.....	.....	.....	.....	.....	.....	.....	.....
55...	5778	42.8	7.0	7.0	6.8	7.9	3.2	3.1	2.9	2.9
57...	5667	38.3	.....	.....	8.4	.....	.....	.....	.....	.....
60...	5515	32.1	12.0	12.0	12.3	11.7	5.1	6.3	8.6	10.1
62...	5440	28.9	.....	.....	16.6	.....	.....	.....	.....	15.0
65...	5321	23.9	21.0	21.4	24.3	15.2	14.6	13.2	20.9	22.7
67...	5247	21.1	25.5	27.2	30.5	17.0	23.1	17.0	28.0	27.1
70...	5160	18.0	32.8	38.9	39.9	19.9	29.8	22.9	36.0	33.2
72...	5084	16.0	37.5	47.3	46.0	21.6	52.2	26.6	39.1	35.6
74...	.....	.....	.....	.....	.....	.....	.....	.....	41.8	36.4
75...	4985	13.4	45.5	61.0	54.2	23.7	68.9	30.7	42.0	37.0
76...	.....	.....	.....	.....	.....	.....	.....	.....	42.1	36.8
77...	4921	12.0	50.8	70.0	58.6	24.8	77.5	32.8	42.0	35.9
80...	4838	10.3	57.5	82.0	63.8	25.7	87.0	33.8	38.2	34.0
82...	4791	9.2	61.2	90.4	66.2	25.9	90.5	33.9	34.9	31.3
85...	4711	7.9	66.8	98.0	.....	25.8	93.0	33.2	29.1	28.0
86...	.....	.....	68.1	.....	68.0	25.5	.....	.....	.....	.....
87...	4666	7.2	69.1	101.6	.....	.....	92.8	32.5	25.8	25.6
88...	.....	.....	69.9	101.8	68.4	25.0	.....	.....	.....	.....
90...	4599	6.2	69.9	100.6	67.0	24.0	89.5	31.0	20.1	21.4
91...	.....	.....	69.1	.....	.....	.....	.....	.....	.....	.....
92...	4557	5.5	.....	95.9	63.3	22.9	86.0	29.8	17.0	18.4
95...	4499	4.9	62.5	85.0	57.0	20.8	79.1	28.0	12.8	15.0
97...	4460	4.2	57.5	76.0	51.3	19.5	74.2	26.7	10.5	12.9
100...	4417	3.7	48.7	60.2	43.0	17.8	66.0	24.7	8.1	10.5
102...	4374	3.4	43.1	51.2	37.6	16.4	61.0	23.3	6.9	9.5
105...	4324	3.1	35.0	39.3	30.2	14.6	54.1	21.2	5.2	6.9
107...	4294	2.9	30.1	32.9	26.0	13.5	49.2	19.9	4.3	5.8
110...	4254	2.6	23.5	25.0	20.3	11.8	42.9	17.7	3.7	4.2

TABLE III

MAXIMUM SENSITIVENESS OF 8 CELLS

Cell	K-H No. 1	K-H No. 2	K-H No. 3	K	Na	Na-H	Rb	Rb-H
Potential-difference.....	129	153	160	149	142	165	140	118
Wave-length $\mu\mu$	446	449	448	437	439	430	478	468
Max. photo-sensitiveness....	9.310^{-8}	12.4	8.3	3.3	11.7	4.7	2.6	2.4

the energy incident on the photo-electric cell per second was $0.058 \cdot 6.8 = 0.394$ ergs; hence one erg of light of wave-length 464 $\mu\mu$ produces a current of $1.22 \cdot 10^{-7}$ amperes. For the same cell, K-H No. 2, the maximum sensitiveness is found at 449 $\mu\mu$ and is $1.24 \cdot 10^{-7}$ amperes per erg. In this way the numbers of Table II were used for each cell and the system of curves was obtained as shown in Fig. 2, in which the abscissae represent wave-lengths in $\mu\mu$, and the ordinates multiplied by $6.9 \cdot 10^{-10}$ give the currents in ampere per erg.

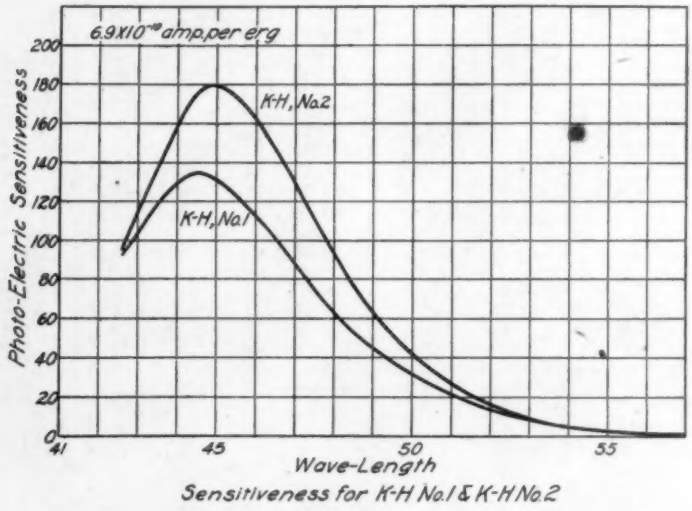

FIG. 2

Pohl and Pringsheim, who measured the sensitiveness of sodium cells, give 2.10^{-12} amperes per "Lichteinheit" for a wave-length of 436 $\mu\mu$. We compared also the measurements of Elster and Geitel with our own results; with a few exceptions there is good agreement in the nature of the curves.

SUMMARY

Eight cells of potassium, sodium, and rubidium were examined. The maximum sensitiveness is of the order of magnitude of 10^{-7} ampere per erg by using rather low potential-differences. By an increase of the voltage much higher values can be obtained, but

the deflections become less stable. Three potassium-hydrogen cells have about the same sensitiveness at the same wave-length. This maximum appears to be shifted toward longer wave-lengths with

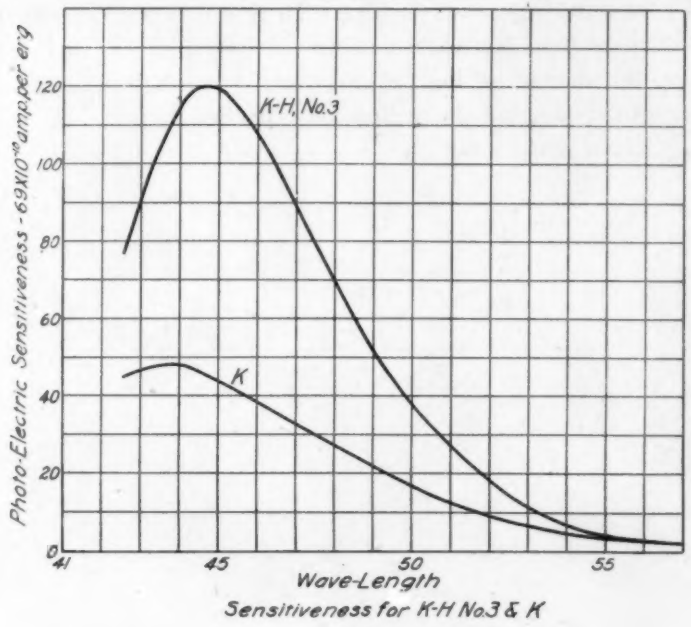

FIG. 3

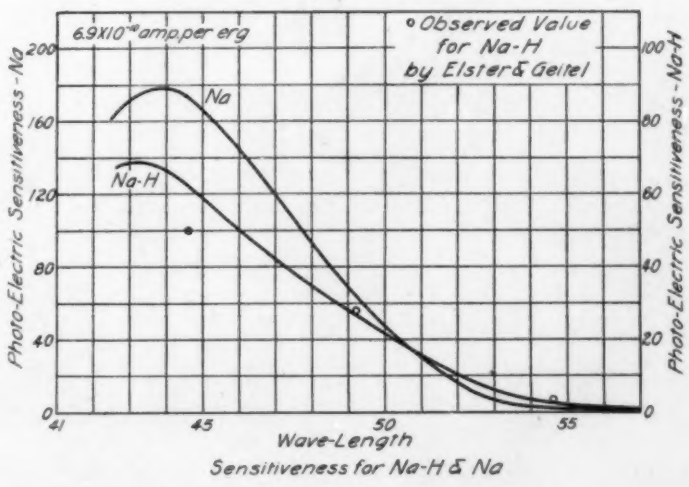

FIG. 4

respect to the maximum of pure potassium. Moreover, the sensitiveness-curve of K-H is more pronounced than that of pure K, which is flatter. On the contrary, the H compounds of Na and Rb shifted the maximum toward shorter wave-lengths as compared with the pure metals, and the sensitiveness-curves of the alloys are flatter than those of the metals themselves. This strange difference in the properties of K, on one hand, and Na and Rb, on

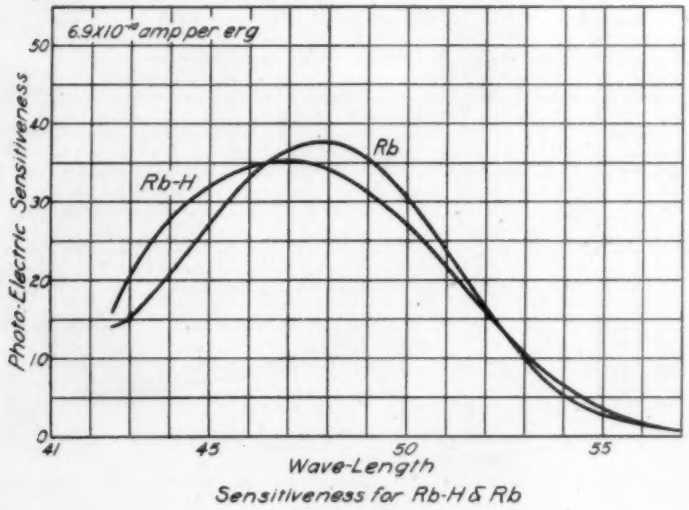

FIG. 5.

the other, requires a continued study of a larger number of cells. This study will also include lithium and caesium and will be extended in the ultra-violet region. It would be interesting to know whether the hydrogen affects the limit for long wave-length of the photo-electric effect of alkali metals. For comparative photometry the color-sensitiveness of the photo-electric cell, of the photographic plate, and of the human eye is required.

The writer wishes to thank Professor A. P. Carman for the facilities of the laboratory, and to acknowledge his indebtedness to Jacob Kunz, under whose direction this work was carried out, for his many valuable suggestions concerning the conduct of the experiment.

PHYSICAL LABORATORY
UNIVERSITY OF ILLINOIS, URBANA
March 12, 1919

STUDIES BASED ON THE COLORS AND MAGNITUDES IN STELLAR CLUSTERS

TWELFTH PAPER: REMARKS ON THE ARRANGEMENT OF THE SIDEREAL UNIVERSE[1]

By HARLOW SHAPLEY

I. THE GENERAL GALACTIC SYSTEM

1. *Introduction.*—A fairly definite conception of the arrangement of the sidereal system evolves naturally from the observational work discussed in the preceding *Contributions*. We find, in short, that globular clusters, though extensive and massive structures, are but subordinate items in the immensely greater organization which is dimly outlined by their positions. From the new point of view our galactic universe appears as a single, enormous, all-comprehending unit, the extent and form of which seem to be indicated through the dimensions of the widely extended assemblage of globular clusters. The fundamental nature of the galactic plane, in the dynamical structure of all that we now recognize as the sidereal universe, is manifested by the distribution of clusters in space. Near this plane lie the celestial objects that we customarily study. The open clusters, the diffused and planetary nebulae, the naked-eye stars, most variables, the objects that define and compose the star streams—all of these appear to be far within a relatively narrow equatorial region of the greater galactic system, a region in which globular clusters are not found. The Orion nebula and even the Magellanic clouds are miniature organizations in this general scheme, and undoubtedly are dependents of the Galaxy.

The adoption of such an arrangement of sidereal objects leaves us with no evidence of a plurality of stellar "universes." Even the remotest of recorded globular clusters do not seem to be independent organizations. The hypothesis that spiral nebulae are separate galactic systems now meets with further difficulties. So long as the high velocities of nebulae were unapproached by the

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 157.

motions of other objects and the maximum luminosity attainable by stars was beyond estimate, and so long as the diameter of the galactic system was thought to be only a thousand light-years or so, we had a fairly plausible case for the "island universe" hypothesis. But now we must consider radial velocities of several hundred kilometers a second as quite possible for objects in our own system; we must assume a moderate upper limit of luminosity, perhaps even for the most massive of novae; and any external "universe" must now be compared with a galactic system probably more than three hundred thousand light-years in diameter. As seen from the center of the galactic system, globular clusters would be distributed in the sky much as the spirals are when observed from the earth.

It is probable that the further accumulation of observations will modify to some extent the views outlined above and discussed more fully in the following pages. The present data may in some cases be susceptible of alternative interpretation, or possibly the conclusions may be questioned in the belief that the material is insufficient. But the greater part of the hypothesis proposed is merely the most direct and simple reading of recent observations.

2. *Outline of interpretation.*—The suggested plan of the galactic system may be concretely formulated through the following series of propositions; some of them are later amplified in so far as seems necessary; for others the discussion of preceding contributions will suffice. A few of the statements are obvious corollaries, while those designated B and F, in some of their details, may be less easy to maintain. Taken altogether they attempt to establish a general idea of the arrangement, extent, and constituency of the system of stars and nebulae.

A. The globular clusters are a part of the galactic system and knowledge of their distances seems at present to afford the best way to fathom the system.

B. The system of globular clusters, which is coincident in general, if not in detail, with the sidereal arrangement as a whole, appears to be somewhat ellipsoidal. The longest axis of the ellipsoid lies in the galactic plane and passes the sun at a distance of approximately three thousand parsecs. Its nearest point is in

galactic longitude 240°, nearly coincident with the direction of the center assigned to the local system of stars. See F and Fig. 1.

C. The center of the sidereal system is distant from the earth some twenty thousand parsecs in the direction of the constellation Sagittarius; it lies in the galactic plane, which dynamically and statistically appears to be the symmetrical plane of the entire sidereal universe as now known. As seen from the sun the thinnest part of the Milky Way lies in Gemini, Taurus, and Auriga—a region rich in bright open clusters close to the galactic plane.

D. The axes of the system in the galactic plane and perpendicular to it may not differ greatly; but the gravitationally important equatorial segment, which apparently contains most of the stars, is at least thirty times as extended in the plane as at right angles thereto.

E. The equatorial region appears to be uninhabitable by compact systems, such as globular clusters, notwithstanding the greater abundance there of stellar material.

F. The stars in the neighborhood of the sun (practically all that go into our catalogues of spectrum, position, and motion) appear to compose (1) a large, open, moving subordinate group, and (2) a part of the surrounding and interpenetrating star fields of the equatorial segment of the greater galactic system. The center of the local system is in the direction of the constellation Carina, nearly at right angles to the direction of the center of the general galactic system, but less than one two-hundredths as far away. The plane of symmetry and condensation of the local cluster is inclined to the galactic plane about 12°; the center of the cluster is north of the galactic plane, and the sun is north of both planes.

G. The volume of space occupied by stars brighter than the sixth apparent magnitude, some of which, being absolutely very bright, are extremely distant as compared with the majority of naked-eye stars, is at most only a hundred-thousandth of the volume occupied by the other parts of the galactic system.

3. *Relation of present interpretation to earlier hypotheses.*—In order to show where the earlier working hypotheses stand with

respect to the interpretation now offered, it may be of interest to note the development, during the course of this work on clusters and variable stars, of the ideas concerning the relation of globular clusters to the galactic organization. Until the last year or so most students of stellar problems believed rather vaguely that the sun was not far from the center of the universe, and that the radius of the galactic system was of the order of 1000 parsecs. From the earlier observational data Seeliger and Newcomb derived a fairly central position for the sun. Hertzsprung[1] in 1906 estimated the "Dimensionen" of the visible Milky Way system to be of the order of 2000 parsecs, and some years later Walkey,[2] from consideration of extensive distributional data, estimated a distance of about seventeen hundred parsecs for the galactic main stream. In 1914, referring to the apparently lens-shaped sidereal system, Eddington[3] wrote, "There is little evidence as to the sun's position with respect to the perimeter of the lens; all that we can say is that it is not markedly eccentric"; and the diameter of the whole system (possibly excluding the peripheral ring of galactic clouds) was placed at some two or three thousand parsecs, with emphasis on the uncertainty. For a later computation Eddington[4] assumed the distance of the Milky Way to be 2000 parsecs.

The work on the hypothetical parallaxes of Cepheids and O-type stars by Hertzsprung, and of eclipsing binaries and Cepheids by Professor Russell and the writer, began to give concrete numerical expression to the distances of remote galactic objects, and in 1914 we have the statement:[5] "Our 'universe' of stars must be some thousands of light-years in diameter," but the computed radius of 2500 parsecs was reduced to 1200 by allowing for a presumably reasonable and necessary scattering of light in space. The necessity for such a correction seems now definitely to have vanished, but the general conception of the size of the stellar system has not

[1] *Zeitschrift für wissenschaftliche Photographie*, **5**, 106, 1907.

[2] *Monthly Notices*, **74**, 655, 1914.

[3] *Stellar Movements and the Structure of the Universe* (London, 1914), p. 32.

[4] *Ibid.*, p. 261.

[5] Russell and Shapley, *Astrophysical Journal*, **40**, 434, 1914.

materially changed. In his valuable memoir[1] on the B-type stars Charlier states:

> The luminosity of these stars is, indeed, so great that a star of this type, situated—as far as can be concluded—at the limits of our stellar universe, is scarcely fainter than the eighth magnitude. We are thus in the position to get, with the help of the B stars, what might appropriately be called a skeleton image of the Milky Way.

Only one star out of the 800 in Charlier's list is more distant from the sun than 800 parsecs, and a heliocentric sphere of 500 parsecs radius contains 95 per cent of the total number. Again, Charlier states that "the center of this cluster [of B-type stars], which may be assumed to coincide with the center of our stellar universe, is situated . . . . in the Constellation Carina" at a distance of 88 parsecs.[2]

In view of these prevailing beliefs, the working hypothesis that a globular cluster is a wholly distinct stellar system was quite appropriate when in 1915 it was found that the Hercules cluster (Messier 13) is possibly several hundred parsecs in diameter. It appeared then that the galactic system might be a large but subordinate unit, eccentrically situated with respect to the greater aggregation of globular clusters. The great distances of the clusters, the similarity of their stars, in many properties, to those of the Galaxy, and finally the discovery of galactic planes in a number of them, tended to emphasize further the comparability of clusters and our own surrounding galactic system of stars.

Two difficulties stood in the way of a definite hypothesis—the comparatively high condensation at the centers of globular clusters and the uncertainty relative to the constituency and distances of open clusters in the galactic clouds. The study of Messier 11 and of the dense star clouds in its neighborhood revealed the presence of faint blue stars—objects which, unless abnormal in size, must be quite similar in absolute magnitude to members of Charlier's cluster of B-type stars, but at least twenty times as distant as the limits of his group.

[1] *Meddelanden från Lunds Astronomiska Observatorium*, Series 2, No. 14, p. 103, 1916.

[2] *Ibid.*, p. 104.

Evidence was also found that the Milky Way clouds near Messier 11 were greatly extended in the line of sight. For a number of other parts of the Milky Way the study of stars in clusters and clouds indicated analogous conditions, and the conviction grew that the galactic system had an extent of at least 15,000 parsecs along its plane. This left little occasion for the direct comparison with globular clusters, the diameters of which were found by further study to be of the order of 150 parsecs. As a consequence, their relation to the general system was quite uncertain until the present determination of parallaxes and the discussion of the distribution in space indicated the position of globular clusters in the arrangement of sidereal objects and suggested that the actual diameter of the galactic system is of the order of 100,000 parsecs.

4. *The plane of symmetry and the equatorial segment.*—In the figures and discussion of the seventh paper of this series the dependence of globular clusters upon a larger symmetrical organization is definitely shown. Apparently there is no occasion to doubt the identity of the plane of symmetry in this system of globular clusters with the galactic plane defined by stellar condensation and the Milky Way. An agreement within a degree or two of the poles of two distinct and unrelated planes is far too unlikely for consideration. Further, we now know that in distance along the plane many of the globular clusters are nearer to us than stars in the open galactic clusters; and also we note that the distribution of Cepheid variables, as shown in Fig. 3 of the eighth paper, bridges the gap between the distant Milky Way clouds and the local system of stars.

That the equatorial segment is populated by stars throughout its whole extent seems very probable; both the arrangement of the clusters and the appearance of the Milky Way agglomerations support this view. But, owing to the evidence of rifts and divisions in the galactic clouds, it is impossible to suppose uniform stellar distribution or even to assume that the stars everywhere are concentrated progressively toward the medial plane. Stars of the galactic branch in Ophiuchus do not necessarily lie farther from the plane than the semi-width of the equatorial segment, for to be outside this region devoid of globular clusters the parallax of the

stars in the cloud must be less than 0".0001. Globular clusters that appear involved in the edges of the star clouds are almost without exception small and faint, and because of their greater radial distances are therefore clear of the equatorial region that contains the majority of known sidereal objects.

5. *The Milky Way and its asymmetry; regions of maximum star density.*—According to the present view of the galactic system the phenomenon of the Milky Way is largely an optical one. Although the existence of local and occasionally very extensive condensations of Milky Way stars is not denied, the conception of a narrow encircling ring is abandoned. The Milky Way girdle is chiefly a matter of star depth, and its long recognized weakness between longitudes 90° and 180° is now taken to be a reflection of the eccentric position of the sun.

On the basis of the third and fourth diagrams of the seventh paper we estimate provisionally that the limit of the Galaxy is three times greater in longitude 325° than in the opposite direction. This does not require an impossible difference of stellar density in the two directions, even if there is a considerable condensation toward the center. A star of a given absolute luminosity situated in the galactic plane would appear less than two and a half magnitudes fainter at the boundary of the system beyond the center than at the opposite point, which is nearest the sun. The remarkable one-sidedness of the Milky Way has been little considered heretofore in works on stellar distribution. Nort,[1] in studying the Harvard map, has made an important beginning by showing that the star density is four or five times greater in the direction of the southern star clouds than in some of the shallower galactic regions of the north.

The surpassing stellar density in the direction now assigned to the center of the galactic system is particularly remarked by Chapman and Melotte[2] in their study of the Franklin-Adams plates. They state that one plate with center in $\alpha = 18^h$, $\delta = -30°$ covers the Sagittarius region of the Southern Milky Way, and the star clouds on limited portions of it are so thick that in the case of twelve out of the

[1] *Recherches Astronomique de l'Observatoire d'Utrecht*, **8**, 113, 1917.

[2] *Memoirs of the Royal Astronomical Society*, **60**, Part IV, p. 168, 1915.

twenty-five areas counted on it, it was found impossible to count every star shown; the images of the faintest stars in these regions merged into one another forming a continuous gray background. On every other plate of the Franklin-Adams series even the faintest star images shown were separate and distinct, and the counts included all stars visible. The extreme richness of the Sagittarius region may be judged of, then, when it is noticed that the incomplete counts on it show far more stars than are found in any other part of the Milky Way.

The fathoming of the sidereal universe need not long depend on globular clusters alone. If the nearest part of its boundary in the general direction of Auriga and Gemini is not more distant than 30,000 parsecs, no stars in that locality with absolute magnitude of zero or brighter will be fainter than the apparent magnitude 17.5. B-type stars will therefore contribute in future measurement of the extent of the system; and the Cepheid variables fainter than the fourteenth magnitude will in time be fully as valuable as the globular clusters in outlining the diameter and contour of the equatorial segment. As a ready qualitative check of the direction and distance of the center, the blue stars in the Milky Way should persist to a fainter magnitude in the southern sky than in the direction of the anti-center.

The possibly ellipsoidal form of the system of globular clusters is indicated in Fig. 1, which gives a projection on the galactic plane of the 60 clusters for which $R \sin \beta < 15{,}000$ parsecs. If the elongation be accepted as a real characteristic of the stars also, it is evident that the apparently densest star regions, depending on the faintness of the stars involved in the estimate, may lie in a longitude differing considerably from that of the center. The general direction of the galactic center is clearly toward the dense star clouds of Sagittarius and Scorpio; but the adopted galactic longitude, 325°, and the corresponding equatorial co-ordinates of the center, $\alpha = 17^h.5$, $\delta = -30°$, are necessarily approximate.

The statistical center derived by Charlier[1] from B-type stars is in Carina, in longitude 236°, a result referring entirely to the local group (within 500 parsecs of the sun) and not influenced by the arrangement of the general system. Strömberg,[2] from bright stars

[1] *Meddelanden från Lunds Astronomiska Observatorium*, Series 2, No. 14, 1916.

[2] *Astrophysical Journal*, 47, 33, 1918.

of the redder spectral types, finds the dynamical center in longitude 257°. Nort,[1] using stars to the eleventh magnitude on the Harvard map of the sky, gets farther outside the bounds of the local cluster and obtains a maximum stellar density in the Milky Way between longitudes 280° and 290°; he finds a density but one-fifth as great in longitude 120°, the direction of the anti-center. Chapman

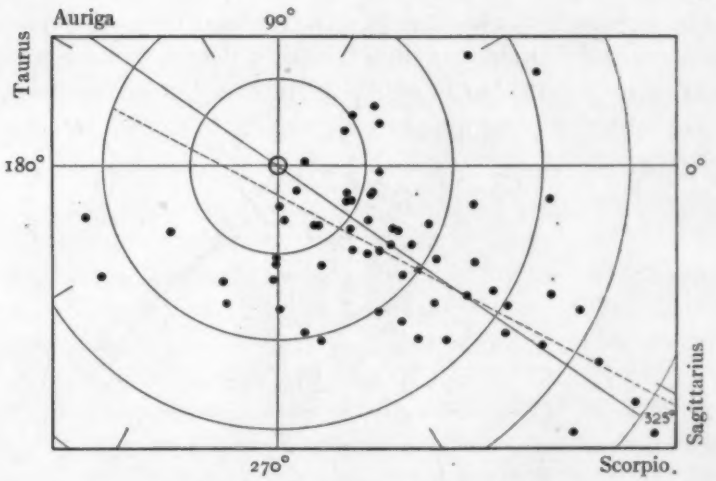

FIG. 1.—The system of globular clusters projected on the plane of the Galaxy. The galactic longitude is indicated for every 30°. The "local system" is completely within the smallest circle, which has a radius of 1000 parsecs. The larger circles, which are also heliocentric, have radii increasing by intervals of 10,000 parsecs. The dotted line indicates the suggested major axis of the system, and the cross the adopted center. The dots are about five times the actual diameters of the clusters on this scale. Nine clusters more distant from the plane than 15,000 parsecs are not included in the diagram.

and Melotte,[2] working to the still fainter limit of the Franklin-Adams plates, find in the clouds of Sagittarius the only region too dense for counting.

This progressive increase of the longitude of maximum star density from 236° to 325° (with the increasing predominance of the general system over the local group), and the appearance to be expected of the star clouds in the directions of the two centers, are

[1] *Op. cit.* [2] *Ibid.*

both in striking agreement with Gould's observations of the brightness of the Milky Way:[1]

> Its brightest portion is unquestionably in Sagittarius [the galactic center]; that in Carina [the local center] being slightly inferior to this as regards intrinsic brilliancy, although far more magnificent and impressive on account of the great number of bright stars with which it is there spangled.

6. *Absence of clusters from the equatorial segment and its dynamical significance.*—In an earlier paper we have remarked that the absence of globular clusters from the mid-galactic region is revealed by the galactic latitudes as well as by the distances from the plane. For the latitudes, however, the wide avoidance of that region is not

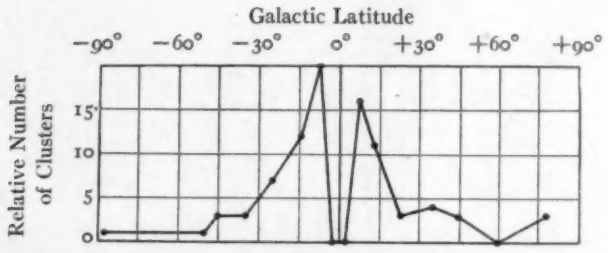

FIG. 2.—Frequency of galactic latitudes, illustrating the mid-galactic region devoid of globular clusters.

so evident, because of the apparent nearness to the plane of some very remote systems. The relative frequency of galactic latitudes, plotted in Fig. 2, shows an equatorial belt 10° in width, which is as yet completely empty of known globular clusters.

It is clear from the figure that any reasonable change in the adopted position of the galactic pole would neither eliminate the segment nor modify its coincidence with the mid-galactic stellar region. It also appears that the region cannot be explained away by supposing the data incomplete through either the failure to record visible globular clusters or the obstruction of light in the equatorial segment. In support of this statement it will suffice to point out that already at a distance of 12,500 parsecs from the sun the absence of clusters is more than chance. Then, first, the suggestion that clusters have been overlooked is absurd, for

[1] *Uranometria Argentina*, p. 370, 1879.

some of the stars in globular systems at that distance would be photographically brighter than the fourteenth magnitude. That is, the overlooked clusters would be more conspicuous than Messier 3. In the second place, if general scattering of light is to account for the absence of clusters, typical stars with negative color-indices should not be found in the Milky Way when fainter than the fifteenth magnitude, for at the distance of 12,500 parsecs $m-M=+15.5$. But such objects have been observed; and, moreover, it is highly improbable that the millions of Milky Way stars fainter than the eighteenth magnitude are all dwarfs.

We have referred to the equatorial segment as a region of avoidance. Slipher's observations of radial velocities suggest that the term is scarcely appropriate, since seven out of ten systems are approaching the sun (and probably the galactic region) with conspicuous velocity.[1] The segment seems rather to be a region of attraction and demolition, and if further work on radial velocities confirms the present indication of systematically high speeds of approach, a factor of very great importance in the evolution of the galactic system will be established.

Table I contains information relative to the ten clusters of measured radial velocity. The observed values in the third column and the computed quantities based upon them in the last column are admittedly provisional. The observed photographic magnitudes in the fourth column, taken from Table II of the seventh paper, show that two of the largest velocities pertain to the faintest and probably most difficult objects. The last column gives the observed radial velocity, V_r (expressed in the unit of 100 parsecs per million years), divided into the radial distance.

The present evidence suggests that globular clusters as a class may be falling rapidly into the regions rich in stars. None of the clusters in Table I is necessarily receding from the plane, for the positive velocity of Messier 5 is far within the uncertainty of the observation, and Messier 9 and 28 are in such low galactic latitudes that the radial component is no test of the true direction of motion perpendicular to the Milky Way. With the possible exception of Messier 5, therefore, all these clusters, with latitudes high enough

[1] *Popular Astronomy*, **26**, 8, 1918.

to make it probable that the radial and perpendicular components have the same sign, are approaching the galactic plane with a speed that unless rapidly diminished will bring most of them to the dense stellar regions in less than 150 million years (cf. last column of Table I). Such an interval of time seems relatively short in the history of a stellar system, and hence these negative velocities make still more remarkable the absence of globular clusters from the equatorial segment.

TABLE I

RADIAL VELOCITIES OF GLOBULAR CLUSTERS

CLUSTER		RADIAL VELOCITY	MEAN PG. MAG. 25 BRIGHTEST STARS	GALACTIC		DISTANCE (UNIT IS 100 PARSECS) R	DISTANCE FROM GALACTIC PLANE $R \sin \beta$	$\frac{R}{V_\beta}$ (UNIT IS A MILLION YEARS)
N.G.C.	Messier			Long. λ	Lat. β			
		km		°	°			
5024...	53	−170	15.07	307	+79	189	+186	110
5272...	3	−125	14.23	8	+77	139	+135	110
5904...	5	+ 10	13.97	333	+45	125	+ 88	.....
6205...	13	−300	13.75	26	+40	111	+ 71	40
6333...	9	+225	15.61	334	+ 9	250	+ 39	.....
6341...	92	−160	13.86	35	+34	123	+ 69	80
6626...	28	0	14.87	336	− 7	185	− 23	.....
6934...	.....	−350	15.78	20	−20	333	−114	90
7078...	15	− 95	14.31	33	−29	147	− 71	150
7089...	2	− 10	14.61	22	−37	156	− 94	1600

7. *Possible explanation—a provisional hypothesis.*—There appears to be no very obvious or reasonable escape from the conclusion that some clusters at least are destined to enter the mid-galactic region. Revolution around the whole system is dynamically improbable; moreover, the present distances from the plane are small as compared with the mean equatorial diameter of the cluster system. With such great velocities and masses it seems incredible that clusters would not easily pass through the stratum of stars. Further observation may reveal survivors receding from the galactic plane, and we may be able to examine them for the effects of the passage.[1]

[1] The galactic latitudes of the large and small Magellanic clouds are 32° and 44°; their velocities of recession, according to observations by Wilson at the D. O. Mills Observatory, probably are 260 km/sec. and 150 km/sec., respectively. Reasonable estimates of the distance (cf. eleventh paper) give 70 and 130 as corresponding values of R/V_β in millions of years.

There is, however, suggestive though incomplete evidence that globular clusters are disrupted upon approaching the mid-galactic regions. As a general but not infallible rule, the clusters at moderate or high distances from the Galaxy are compact; the nearer ones are open. There is, for example, the well-known contrast between ω Centauri and 47 Tucanae, the two brightest and nearest systems, the former 1800 and the latter 4700 parsecs from the plane. Of the five systems within 2000 parsecs of the galactic plane four are decidedly open for globular clusters (Table II). The fifth, Messier 62, shows a structural irregularity that may be an indication of rupture; its parallax, depending only on its diameter, is perhaps inaccurate because of asymmetry.

TABLE II

GLOBULAR CLUSTERS NEAREST THE GALACTIC PLANE

N.G.C.	Galactic Latitude	$R \sin \beta$ (Parsecs)	Remarks
4372.....	− 9°	−1800	Large, faint, and little condensed. "Rather faint at center."—Melotte.
5139.....	+16	+1800	ω Centauri. Not strongly condensed.
6266.....	+ 7	+1900	M. 62. Well condensed but probably the most asymmetrical of globular clusters. See Bailey, *Harvard Annals*, **76**, 74, 1916.
6397.....	−12	−1700	Large cluster and one of the nearest. "Stars rather scattered."—Melotte.
6656.....	− 9	−1300	M. 22. The most open of large globular clusters.

The distribution of stars in open galactic clusters is possibly a second indication of the dissipation of globular clusters in the Milky Way. The diameter of some open clusters appears to be quite comparable with that of globular clusters. Several of them contain mainly stars that are highly luminous and probably of great mass. Counts in the surrounding star fields have shown in certain cases (Messier 67, Messier 11, h and χ Persei,[1] the Pleiades[2]) that the cluster stars are sparingly scattered over an area several times greater than that of the nucleus.

[1] Inferred from radial velocity results by Adams and van Maanen, *Astronomical Journal*, **27**, 187, 1913.

[2] Trümpler, *Popular Astronomy*, **26**, 9, 1918.

As a provisional working hypothesis, which is supported by numerous observed conditions and may be further tested without difficulty, it is suggested that the obvious dynamical equilibrium of a globular cluster has been acquired originally at a great distance from external perturbing forces and is an extremely delicate adjustment that quickly breaks down under stresses such as those prevailing in the galactic region; further, that faint stars in globular clusters are of small mass and of more than average velocity (analogy with galactic stars), and in their orbital motions frequently attain great distances from the center. When the globular cluster approaches a disturbing body as massive as the general galactic system, such stars are of course most readily lost and intermingled with galactic stars.[1] On the other hand, the massive cluster stars, which are mostly of high luminosity, having low peculiar velocities and maintaining in their subsystem a high degree of stability, retain their organization longer in a disrupting field and, except for rare and accidental encounters with galactic stars, undergo as a single unit the general perturbations of the galactic system. It appears necessary to suppose that the gravitational or electrical field near the plane of the Milky Way is by itself more potent in the acceleration of stellar velocities than are near approaches; otherwise it seems impossible that through chance dynamical encounters a massive globular cluster, highly organized and presumably in a steady state, should be so speedily dissipated and transferred into an open galactic group.

8. *Remarks on the contraction theory of stellar evolution.*—In a preceding paragraph we have alluded to the scale of time in the development of the galactic system. An observational contribution to this problem, and more directly to the problem of the speed of evolution of spectral type, is afforded by the distant clusters. Recent discussion by Lindemann, Joly, Véronnet, Eddington, and Jeans, relative to the probable age of the earth and the sun from the standpoint of the contraction theory, emphasizes the persistent disagreement between this theory and the data of geology and physics in estimating the interval of time since the deposition of

[1] A somewhat similar problem has been examined analytically by Jeans; in fact, he may have had this identical hypothesis in mind (*Monthly Notices*, **76**, 560, 1916).

the earliest sedimentary rocks. Lindemann and Jeans have argued that allowance for known radioactive or even for all electrical properties of matter cannot have prolonged the apparent constancy of solar radiation sufficiently to meet geological requirements. Specifically, Eddington computes that the duration of the total giant stage of a star, if contraction is its source of energy, is not likely to exceed one hundred thousand years; the development from a giant M to a giant G should be less than twenty-five thousand years. To obtain an appreciably slower development we must call upon sources of energy now unrecognized.

Giant stars of various spectral types are numerous in globular clusters and are easily studied in relation to the foregoing problem. We recall that, owing to the finite velocity of light, our investigations of clusters do not relate to contemporaneous conditions, but rather to events of the remote past. Stars in the nearest globular cluster are actually two hundred centuries older at present than they appear in our records, and the light we now receive from the most distant systems has been en route about two hundred thousand years. A significant consequence of these unlike distances, thanks to the structural uniformity of stars and of globular clusters, is that we are able to compare phenomena separated by enormous intervals of time. Instead of having to test stellar development observationally through the dissimilar records of one century or possibly two, with globular clusters we may make a test under identical conditions of climate and instrumental equipment at intervals up to more than a thousand centuries.

The clusters range in distance from twenty thousand to more than two hundred thousand light-years. The farther away the younger they are in our study and the less developed are their stars. (We assume, of course, that distance from the earth is totally irrelevant in the birth time of a globular cluster, though distance from the galactic center may not be.) The results at hand, though preliminary, are apparently decisive; and, as regards definite indications of evolution, are uniformly negative. We note, in particular, the conclusions reached in the eleventh paper, that no measurable change has occurred even in the 180,000 years

separating the phenomena recorded for the nearby Hercules cluster and for the most distant system known.

It would have been impressive to find with decreasing distance and increasing age a progressive change in stellar conditions, thus enabling us to use this time scale to its greatest advantage. Perhaps, however, our negative result may be quite as important—our evidence, that is, of essential contemporaneousness from cluster to cluster. The result suggests the insufficiency of the contraction theory, thus supporting the geological time scale on the earth; it contributes observationally to the growing belief that stellar radiation involves sources of energy that are as yet wholly unknown; and, by indicating that an interval of 100,000 years is insufficient to show appreciable stellar development, it tends to alter our conceptions of the speed of evolutionary change.

II. THE LOCAL SYSTEM

9. *Discrepancy of centers—its interpretation.*—As has been stated above, the galactic center deduced from the arrangement of clusters, and roughly corroborated by the density of the Milky Way clouds, is about 90° from the center recently assigned by Walkey and Charlier on the basis of statistical discussions of the bright stars near the sun. The new position is not far distant, however, from the direction toward and from which catalogued stars show a preferential drift. To investigate this discrepancy of centers and the possible meaning of the star drifts in the mechanics of the general galactic system we are led to inquire what part the local stars play in the larger scheme. Let us consider the stellar phenomena manifested in our neighborhood from the standpoint of the greater galactic organization and think of the local stars as forming a group which is imbedded in an extensive stellar stratum and subordinate to the gravitational influences of the major system. Such a procedure brings us to the following hypothesis, which promises fairly satisfactory interpretations of a number of observational results, and appears to harmonize some of the earlier theories as to the systematic motions of the stars:

In the neighborhood of the sun (within 1000 parsecs) the stars fall into two categories: (1) Members of the general galactic system, having motions, distribution, frequencies of spectral type, and absolute magnitude, much the same as are believed to prevail throughout the greater part of the equatorial segment; these we shall call field stars. (2) Members of a moving local system of limited extent; these we shall call cluster stars.[1] The cluster is receding in a nearly radial direction from the center of the galactic system and is surrounded by and intermingled with the field stars. It is concentrated toward a plane of symmetry, which is inclined about 12° to the galactic plane as defined by remote non-cluster stars and the clouds of the Milky Way. Its motion of translation apparently is parallel to the Galaxy rather than to its own equator; and there is, in addition, an internal motion in the cluster with respect to its center which appears to be about fifty parsecs north of the true galactic plane. The sun, evidently a field star, is at some distance laterally from the center of the cluster and a few parsecs above its central plane of symmetry. Cluster stars comprise nearly all of the B-type and a decided majority of the A-type stars brighter than the seventh magnitude and a large percentage of the redder stars within three or four hundred parsecs of the sun. The field stars within this limit include very few B's, a small percentage of A's, and possibly a majority of the redder spectral types. Cepheids, N-type stars, most of the O-type stars, the Ursa Major group, planetary nebulae, and stars of peculiarly high random velocity are probably all members of the field, which is, in general, a heterogeneous mixture of many groups and tendencies.

10. *The local cluster.*—In discussing the foregoing hypothesis the most important object will be to demonstrate the existence of a large, local, definitely organized cluster; for when we have satisfied ourselves that there is such a group moving in the neighborhood of the sun, and have admitted the reality of an extensive and populous galactic system, the present hypothesis appears to afford the most simple and natural explanation of the observed motion and distribution of local stars. As an analogy suppose we consider

[1] For a slight modification of the following theory of star-streaming see Section IX of *Mt. Wilson Contr.* No. 161.

the compactly organized galactic cluster Messier 11, which is deeply immersed in the rich star clouds of the Milky Way. Unless it be completely at rest with respect to its surroundings, its motion, as seen from a random-moving field star within its bounds, would give rise to exactly such phenomena as the systematic stellar motions we observe in our neighborhood.

We start from the well-known observational results that stars of spectral type B are much alike in actual luminosity, that they are much brighter than the average star, and that with decreasing apparent magnitude they do not increase in number as rapidly as other types of stars. A consideration of the star ratio shows that beyond the distance corresponding to apparent magnitude 7.5 the B stars must be very infrequent.[1] Charlier, computing the average luminosity of the early subclasses of this type, has derived the distance and distribution in space of all such stars contained in the Harvard catalogues and has given striking evidence that they form a large system consisting of about eight hundred stars, among which the sun is eccentrically situated. These two results by themselves seem to show the existence of an important local aggregation. But there is much additional evidence.

11. *Central plane of the B stars and its relation to the Galaxy.*—The first problem to be investigated is whether the system of bright B stars is other than a normal arrangement of galactic stars in the extensive equatorial segment. To determine the position of the central plane of the B-type group Charlier used 751 stars (without differentiation as regards distance from the sun) and obtained for the co-ordinates of the pole: $\alpha = 184°.3$, $\delta = +28°.7$. This position he adopts as the pole of the Milky Way,[2] considering it in satisfactory agreement with the pole of the plane defined by the Milky Way clouds: $\alpha = 191°.2$, $\delta = +27°.4$. Apparently he identifies the "Galaxy of B stars" with the entire stellar universe—a procedure that cluster studies obviously do not support, for only a few of the stars in Charlier's group are more distant from the sun than five hundred parsecs.

[1] Cf. discussion by Seares, *Publications of the Astronomical Society of the Pacific*, 30, 114, 1918.

[2] *Op. cit.*, pp. 40 and 43.

If, however, the difference in the positions of the two poles be real, an inclination of the central plane of the B-type system to the Galaxy is indicated, and we have an additional argument for its existence as a distinct cluster. The diagrams in Charlier's memoir show, moreover, that the adopted plane is far from satisfying the distribution of the nearer B stars. In Fig. 3, which is based on data (Table III) derived from Charlier's tabulated results, the median values of Z, distance from the adopted central plane, are plotted for successive intervals of Y, that component of the

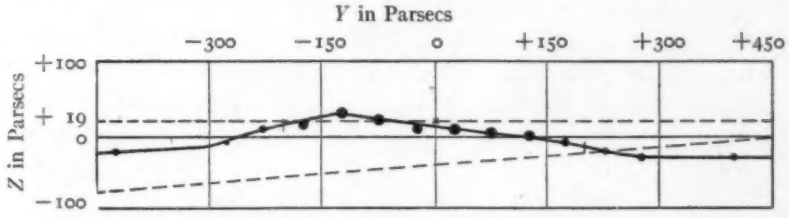

FIG. 3.—Projection of the local cluster of B stars on a plane perpendicular to the Galaxy and to the projection, on Charlier's adopted plane, of the line joining the sun and the center of the cluster. The center of the system of B stars, as derived by Charlier, is at the origin of co-ordinates. The cross shows the position of the sun. The true galactic plane is indicated by the inclined broken line. Vertical lines across the curve show the limits of distance adopted for the solution represented by Fig. 4.

distance in the plane which is perpendicular to the direction of the center from the sun. The area of each of the plotted points is proportional to the number of stars entering the median value and illustrates the rapid falling off of star density beyond a certain distance. The unit used by Charlier, the siriometer, is nearly equivalent to five parsecs or sixteen light-years. A cross indicates the position of the sun. The broken horizontal line represents the projection of the galactic plane adopted by him. The majority of B stars obviously lie below it, proving the sun's position to be above the cluster's central plane. The full horizontal line indicates the central plane adopted by Charlier; but considering only the inner part of the cluster we observe that the sun is much nearer to the central plane. The inclined broken line shows the projection of the galactic plane as derived from the stars of the Milky Way clouds; its inclination and its distance below (south of) the B

cluster and the sun are derived from the results mentioned on a following page. The figure suggests in general that a few B stars of the Galaxy are sparingly intermixed with a definite and limited cluster.

TABLE III

Intervals of Y in Siriometers	Number of Stars	Median Z in Siriometers
$\leqq -60$	41	-4
-59 to -50	16	-2
-49 " -40	52	$+2$
-39 " -30	59	$+3$
-29 " -20	72	$+6$
-19 " -10	80	$+4$
-9 " 0	83	$+2$
0 " $+9$	88	$+2$
$+10$ " $+19$	76	$+1$
$+20$ " $+29$	70	0
$+30$ " $+39$	60	-2
$+40$ " $+49$	37	-4
$+50$ " $+59$	36	-6
$\geqq +60$	35	-6

12. *Summarized discussion of the properties of the local cluster.*— The procedure from this point involves much computational work and statistical discussion, and for the present the most relevant results can best be given in a summarized form.

a) Charlier's determination of the mean absolute magnitudes of B stars is compared in Table IV with averages derived from the

TABLE IV

Spectral Class	Kapteyn		Charlier		Difference
	Number of Stars	Absolute Magnitude	Number of Stars	Absolute Magnitude	
Bo*	36	-0.34 ± 0.23	27	-0.56	$+0^{M}.22$
B1	23	-2.00 ± 0.16	26	-2.76	$+0.76$
B2	36	-1.21 ± 0.16	40	-2.76	$+1.55$
B3	148	-0.38 ± 0.06	157	-1.10	$+0.72$
B5	67	-0.21 ± 0.09	104	-1.29	$+1.08$

* In Kapteyn's lists B stands for Bo. The lack of homogeneity in this subtype, noted by both investigators, may be due to the inclusion of some (fainter stars) of the general class B with the true Bo stars.

parallaxes given by Kapteyn in *Mount Wilson Contributions*, Nos. 82 and 147. While systematically fainter, Kapteyn's mean values

verify the similarity of the subclasses Bo, B3, and B5, and the much greater average luminosity of B1 and B2.

b) If we desire to limit our investigation of the B stars to the denser part of the group (say, to approximately two hundred parsecs from the sun, as indicated in Fig. 3), we should include only those brighter than apparent magnitude 4.0 for types B1 and B2, and brighter than 5.5 for types Bo, B3, and B5. Such data permit a solution for the equatorial plane of the B cluster that is not seriously influenced by outside stars.

c) From the several lists in *Harvard Annals*, **56,** the galactic longitudes and latitudes have been discussed for 356 B-type stars falling within the foregoing limits of spectrum and brightness. The results, collected in Table V, give for the pole of the central plane of the flattened B-type cluster: $\alpha = 178°$, $\delta = +31°.2$.

TABLE V

Intervals of Galactic Longitude*	No. of Stars	Median Galactic Latitude	Mean Galactic Latitude	Residual from Curve
0°– 9°	15	+10°	+12°	+ 2°
10 – 19	13	+ 6	+ 8	– 1
20 – 29	19	+ 8	+11	+ 3
30 – 39	26	+ 8	+ 5	– 1
40 – 49	16	+ 2	– 5	–10
50 – 59	22	+ 4	+ 7	+ 4
60 – 69	22	+ 2	+ 3	+ 2
70 – 79	15	+ 4	– 1	0
80 – 89	26	– 1	– 3	– 0
90 – 99	13	– 3	– 2	+ 2
100 –109	14	–19	–17	–11
110 –119	24	– 8	– 4	+ 4
120 –129	20	–10	– 9	+ 0
130 –139	39	–16	–10	+ 1
140 –149	18	– 2	–11	+ 0
150 –159	14	– 6	–10	+ 2
160 –169	20	–16	–10	+ 2
170 –179	20	–16	–14	– 3

* Diametrically opposite regions are combined for this table.

d) The definiteness with which this secondary Galaxy is determined is shown in Fig. 4, where mean galactic latitudes are plotted against galactic longitude. The semi-amplitude of the resulting sine-curve yields 12° for the inclination of the two planes, and the nodes are in galactic longitudes 70° and 250°. The dip of the

central plane due to the sun's position to the north is 5°. If stars in the constellation of Orion were deleted from the discussion, the result would not be materially affected. The average deviation of a mean value from the curve is +2°.7.

e) A discussion of all A-type stars brighter than the sixth apparent magnitude confirms the foregoing results, showing that other spectral classes are involved in the cluster. The inclination derived from A stars, however, is only about 4°, probably an indication that many general galactic stars are included and also that the concentration to the plane of the cluster may not be so pronounced as for B-type stars.

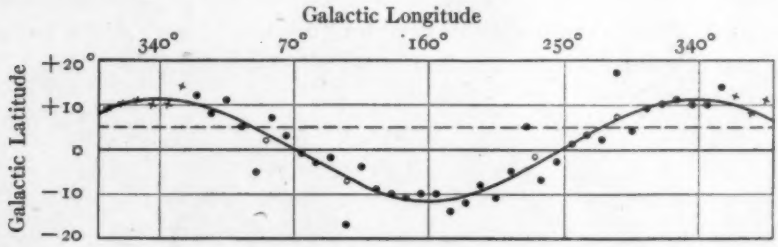

FIG. 4.—Solution for the inclination of the local cluster to the galactic plane

f) We have further suggestions that a majority of A stars probably belong to this limited cluster, first in Plummer's discussion of the preferential motion shown by their radial velocities and second in the observations of Boss and Eddington that the mean parallactic motion of these stars is the same in low and high galactic latitude although the density is twice as great near the Galaxy.

g) In Kapteyn's result that the B stars are members of Stream I we also have an indication that some stars of all the later types belong to the cluster.

> The work thus far done proves the continuity of the series of the B and A and the second-type stars. . . . . Some B stars at least must be regarded as members of the Second Stream. It is now found that the remainder—the overwhelming majority—belong to the First Stream.[1]

Apparently, then, the membership of Stream I is limited wholly to the cluster.

[1] Kapteyn, *Mount Wilson Annual Report*, 1916, p. 256.

h) Gould's belt of bright stars, as revised by Newcomb,[1] is nearly coincident with this secondary Galaxy. A definite trace of it is given by all naked-eye stars when considered together, irrespective of type (lucid red and yellow stars contribute little because of their uniform distribution in the sky); stars of the ninth magnitude, however, give the same pole for the Milky Way plane as is given by galactic clouds (Newcomb).

i) Cepheid variables extend far outside the limits of the local cluster, and the pole of their plane of concentration is identical with that for the galactic clouds (Fig. 5). They afford the best

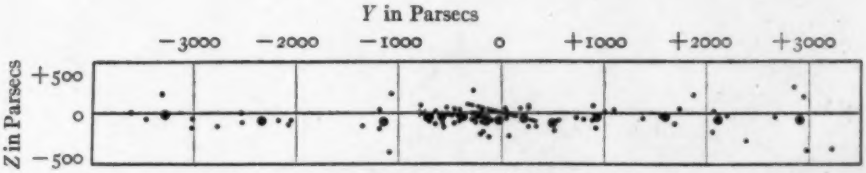

FIG. 5.—Projection of the positions of Cepheid variables on the same plane as in Fig. 3, the sun being at the origin. The small dots represent individual stars, the cross a special group in Carina, and the large dots mean values. The inclined line in the center represents the projected plane and the probable extent of the local cluster of B stars.

determination yet available of the sun's distance north of the galactic plane—about sixty parsecs. A systematic error in the absolute magnitude of Cepheids would affect this distance proportionately, but would not alter the general conclusions. The N-type and most O-type stars are sufficiently remote and concentrated to the plane to afford a check of the sun's displacement, if reliable individual parallaxes become available. The poles of their planes of concentration are apparently identical with the pole derived from the galactic clouds.[2]

j) The center of the B-type cluster, adopting Charlier's values of absolute magnitude, is more than fifty parsecs north of the galactic plane, making the sun less than ten parsecs north of the central plane of the B stars (Fig. 3). For this last quantity Charlier derived 19.2 parsecs, but his work involves extra-cluster stars that

[1] *Carnegie Institution of Washington, Publication No. 10*, 1904.

[2] Hertzsprung, *Astronomische Nachrichten*, **192**, 261, 1912.

apparently are concentrated to the true galactic plane. With Kapteyn's absolute magnitudes of the B's the distance of the cluster's central plane below the sun is still less, and the sun's distance from the local center is less than fifty parsecs.

k) The evidence that the local cluster is a dynamical unit and has conspicuous internal motion superposed upon a translational velocity includes: (1) the behavior of the star ratio for spectral types B and A; (2) the greatly flattened form of the system, at least for the B stars; (3) Kapteyn's announcement of the acceleration of Stream I;[1] (4) Strömberg's evidence from second-type stars of a rotation around a center approximately coincident in direction with the center of the cluster as derived from B stars;[2] and (5) the deviations of the vertices of the various groups of B stars, depending upon position in the sky. A study of the last three points, if not too much constrained by the magnitude of the observational errors, may show whether the internal motion is approximately radial or is a rotation in one general direction or in more than one.

12. *Consequences of motion—star-streaming.*—The foregoing abbreviated account seems to show conclusively that an open cluster surrounds the sun, and that it is comprehensive enough to include stars as numerous and varied as the components of a star stream. The continuity of the galactic star fields beyond the cluster's limits is strongly indicated by the arrangement in space of Cepheid variables (Fig. 5) and other types of distant stars, but especially by the distribution of the faint stars of the Bonner Durchmusterung (Seeliger, Newcomb) and by the increasing galactic concentration with decreasing apparent brightness of still fainter stars (Kapteyn, Seares, Van Rhijn). As seen from the solar system, therefore, the local cluster, if in motion, must inevitably produce star-streaming analogous to that observed; hence it is a natural assumption that the recorded systematic motions of the local stars are due wholly to such a cause. That the translation through the star field is approximately radial is of some dynamical significance, and that it is in the plane of the Galaxy was to be expected. The internal motion, on the other hand, probably

[1] *Mount Wilson Annual Report*, 1916, p. 255.

[2] *Mt. Wilson Contr.* No. 144; *Astrophysical Journal*, 47, 7, 1918.

has a maximum component in the plane of the cluster. Unfortunately the small inclination may make difficult the separation of the two motions.

The present viewpoint of star-streaming seems to be greatly strengthened by the way in which important observed facts agree with its requirements. We have mentioned the form and limits of the cluster, its stellar content, its motion parallel to the galactic plane, the probable acceleration of Stream I, and the distribution of A-type stars. Two or three other points may be referred to here.

a) Since the plane of concentration of field stars lies south of the sun (Fig. 5), the theory requires that stars of Stream II should be relatively less numerous in northern than in southern galactic latitudes. In agreement with this Hough and Halm have found, from both radial velocities and proper motions, that the stars of Stream II are more than twice as frequent near the southern galactic pole as near the northern.[1] This point appears to be of high importance.

b) As the cluster is of limited extent the proportion of field stars should increase with increasing distance from the center. The ratio of the number in the first stream to that in the second is $\frac{3}{2}$ for naked-eye stars (excluding type B); for fainter stars Dyson and Thackeray[2] find the ratio $\frac{4}{3}$. Stars as distant as 1000 parsecs presumably would show only accidental traces of Stream I.

c) The declination of the apex of solar motion should be sensitive, on this cluster hypothesis, to the character and average distance of the stars involved in its determination. Thus the low declinations derived from stars of early types, of large proper motions, of faint absolute magnitude, of bright apparent magnitude, all indicate that the apex with respect to the galactic field lies considerably north of the value commonly used. Dyson and Thackeray's[3] work on Groombridge stars and Comstock's[4] results from the very faint "optical" companions of double stars perhaps most nearly indicate the "true" direction of solar motion.

[1] *Monthly Notices*, **70**, 85, 568, 1910; Halm, *ibid.*, **71**, 610, 1911.

[2] *Ibid.*, **77**, 590, 1917.

[3] *Ibid.*, **65**, 428, 1905.

[4] *Astronomical Journal*, **28**, 54, 1913.

In many of its features the present hypothesis makes no claim to novelty. It includes, indeed, a patchwork of many preceding suggestions, but is of course entirely independent in that the problem has been approached from the point of view of the recently acquired ideas on clusters and on the arrangement and constituency of the larger galactic system. Among earlier deductions and speculations related to this subject we note that Gould, forty years ago, thought his "Belt" of bright stars (inclination 20°, longitude of node 90°) represented a local cluster of possibly four hundred members; but Newcomb's later analysis attributed the whole phenomenon to a few chance aggregations. Hertzsprung and Charlier have found the deviation of the galactic pole for B stars, the former suggesting that the result might be significant. Perrine has noted that one of the vertices lies in the general direction of regions rich in globular clusters. An early hypothesis by Hough and Halm tentatively identified Stream II with the Milky Way stars. Turner's gravitational hypothesis of the streams assigned the center of the universe to the line of star-streaming. Jeans has considered theoretically several different possibilities, some of which resemble the present suggestions. But in developing this interpretation the obligation is by far the greatest to the various discussions of theories and observational data by Eddington and Kapteyn.

If a theory similar to the present one survives the test of future observation and analysis, it will be of interest to note how closely it approaches Kapteyn's original statement of star-streaming, so far as local phenomena are concerned. The "two cloud" hypothesis of the streams—the "dualistic" conception of the universe, as Charlier calls it—would be a more literal view of the conditions near the sun than that given by the ellipsoidal theory of streaming —the "monistic" conception. But so far as we now see the latter may apply better to the galactic system as a whole, and we also have a case for the ellipsoidal theory in the internal motions of the local cluster.

MOUNT WILSON OBSERVATORY
April 1918

THE HELIUM SPECTRUM AND THE UNIT ELECTRICAL CHARGE

By FERNANDO SANFORD

In his paper in *Physikalische Zeitschrift*, **4**, 400 (*Gesammelte Werke*, p. 80), Ritz concludes that all spectral series may be expressed by the formula

$$\pm\gamma = N\left(\frac{1}{p^2}-\frac{1}{q^2}\right),$$

where γ represents the wave-number per centimeter, N the Rydberg constant 109675, and p and q the roots of certain transcendental equations. In the case of the Balmer series this equation takes the form

$$\pm\gamma = N(1/4-1/m^2).$$

Ritz concludes that the constant N is strictly universal, and hence that the wave-numbers of the lines of all spectral series may be expressed in terms of this constant.

In a paper entitled "The Astronomical Atom and the Spectral Series of Hydrogen"[1] the present writer has shown how, on the assumption that radiating electrons are revolving in elliptical or circular orbits about a central positive charge, the central positive charge for any wave-length may be calculated in terms of the wave-length and a numerical constant, viz., $Q = 2.882\cdot 10^{-12}/\sqrt{\lambda}$, where Q is the central charge. It was also shown in the same paper that the Rydberg constant N is the wave-number of an electron revolving about a central positive charge $Q = 2e = 9.548\cdot 10^{-10}$ E.S.U.

This being the case, it should be possible to calculate the effective central charge corresponding to any line of any series to which the Ritz formula may be applied in terms of the charge $2e$ by means of an equation of the form $Q = 2e\sqrt{1/p^2 - 1/q^2}$. This was done for all the known series in hydrogen in the paper referred to above. It is

[1] *Astrophysical Journal*, **48**, 1, 1918.

the purpose of the present paper to show that it may also be done for the six known series in the helium spectrum.

The helium series are usually separated into two groups, sometimes classified as the helium and the parhelium groups. Each group consists of a "principal" series and two "subordinate" series. The two subordinate series of the helium group are made up of double lines, while the corresponding series of the parhelium group consists of single lines. In the present paper the mean wave-length of a pair is taken as the wave-length for which the central charge is computed, though since the value of some of the constants used in calculating our numerical constant $2.882 \cdot 10^{-12}$ is known to only three significant figures, it usually makes no difference in our computed value of Q which wave-length of a close doublet is used.

FIRST SUBORDINATE SERIES, HELIUM GROUP

There is a long series in helium classed by Kayser as the first subordinate series of the helium group, or Group I. This series corresponds to the Balmer series in hydrogen, but whereas in the Balmer series the wave-length of any line may be computed from the equation $1/\lambda = N(1/4 - 1/m^2)$, the corresponding equation for the first subordinate series of helium is

$$1/\lambda = N(1/3.756 - 1/m^2) \text{ or } 1/\lambda = N\left[\frac{1}{(1.938)^2} - \frac{1}{m^2}\right].$$

In order to compute the unit electrical charge by means of this equation, we write

$$Q = 2.882 \cdot 10^{-12}/\sqrt{\lambda} = 2e\sqrt{1/(1.938)^2 - 1/m^2}.$$

The values of $2e$ derived from this equation for each line of the series under consideration are given in Table I.

FIRST SUBORDINATE SERIES, PARHELIUM GROUP

The series of the parhelium group which corresponds to the above series consists of twelve lines which correspond in wave-length with the lines of the Balmer series even more closely than do the lines of the series given in Table I. The value of e may be

TABLE I

UNIT ELECTRICAL CHARGE FROM FIRST SUBORDINATE SERIES OF HELIUM

m	λ	$\frac{2.882\cdot10^{-12}}{\sqrt{\lambda}}$	$2e$
3	5876	3.758	9.538
4	4472	4.310	9.546
5	4026	4.542	9.548
6	3820	4.663	9.548
7	3705	4.735	9.546
8	3634	4.780	9.547
9	3587	4.812	9.548
10	3555	4.834	9.548
11	3531	4.850	9.547
12	3513	4.862	9.546
13	3499	4.872	9.547
14	3488	4.880	9.548
15	3479	4.886	9.547
16	3472	4.891	9.548
17	3466	4.895	9.547
18	3461	4.899	9.549
19	3457	4.902	9.549
		Mean value of $e=4.7735$	

calculated from these lines by the equation $Q=2e\sqrt{1/4.038-1/m^2}$; or, to put the equation in the form used by Ritz, $Q=2e\sqrt{1/(2.0094)^2-1/m^2}$, where, as before, $Q=\frac{2.882\cdot10^{-12}}{\sqrt{\lambda}}$. The results of this calculation are given in Table II.

TABLE II

UNIT ELECTRICAL CHARGE FROM FIRST SUBORDINATE SERIES, PARHELIUM

m	λ	$\frac{2.882\cdot10^{-12}}{\sqrt{\lambda}}$	$2e$
3	6678	3.527	9.546
4	4922	4.108	9.546
5	4388	4.351	9.550
6	4143	4.477	9.546
7	4009	4.551	9.546
8	3927	4.599	9.548
9	3872	4.632	9.548
10	3834	4.655	9.548
11	3806	4.667	9.540
12	3785	4.681	9.544
13	3769	4.690	9.540
14	3756	4.698	9.540
		Mean value of $e=4.7725$	

As is well known, there is in the hydrogen spectrum another series, known as the Pickering series, which converges to the same wave-length, and hence to the same central charge, as does the Balmer series. The wave-numbers of the lines of this series are expressed by the Ritz equation $1/\lambda = N(\frac{1}{4} - 1/(m+0.5)^2$ and their central charges by the equation $Q = 2e\sqrt{\frac{1}{4} - 1/(m+0.5)^2}$.

The two second subordinate series in the helium groups correspond to the Pickering series in hydrogen in that each series converges to the same wave-length and the same central charge as does the first subordinate series of its group.

SECOND SUBORDINATE SERIES, HELIUM GROUP

This series, as generally given, consists of thirteen lines, though the line for which $m=3$ does not fit Rydberg's equation and the value of e calculated from this line differs by a little more than 4 per cent from its true value. The line for which $m=4$ also gives a value of e almost 1 per cent too great.

The wave-lengths of these lines and the value of $2e$ as calculated from them are given in Table III.

TABLE III

UNIT ELECTRICAL CHARGE FROM SECOND SUBORDINATE SERIES, HELIUM

m	λ	$\frac{2.882 \cdot 10^{-12}}{\sqrt{\lambda}}$	$2e$
3	7066	3.428	9.965
4	4713	4.195	9.643
5	4121	4.486	9.585
6	3868	4.631	9.567
7	3733	4.715	9.556
8	3652	4.767	9.553
9	3599	4.802	9.542
10	3563	4.827	9.549
11	3537	4.843	9.530
12	3517	4.858	9.546
13	3502	4.870	9.549
14	3491	4.876	9.546
15	3481	4.882	9.544
		Mean value of e = 4.79	

The values of $2e$ are calculated from the equation

$$\frac{2.882\cdot 10^{-12}}{\sqrt{\lambda}} = 2e\sqrt{\frac{1}{(1.938)^2}-\frac{1}{(m-0.4)^2}}.$$

SECOND SUBORDINATE SERIES, PARHELIUM GROUP

There is also a second subordinate series in the parhelium group which converges to the same wave-length and the same central charge as does the first subordinate series. The value of e may be calculated from this series by using the equation

$$\frac{2.882\cdot 10^{-12}}{\sqrt{\lambda}} = 2e\sqrt{\frac{1}{(2/.0094)^2}-\frac{1}{(m-0.15)^2}}.$$

The results of this calculation are given in Table IV.

TABLE IV

UNIT ELECTRICAL CHARGE FROM SECOND SUBORDINATE GROUP, PARHELIUM

m	λ	$\frac{2.882\cdot 10^{-12}}{\sqrt{\lambda}}$	e
3	7282	3.377	4.782
4	5050	4.056	4.772
5	4438	4.326	4.773
6	4169	4.463	4.783
7	4024	4.543	4.772
8	3936	4.594	4.775
9	3878	4.628	4.775
10	3838	4.652	4.776
11	.....	.....	.....
12	3788	4.683	4.773
13	3771	4.693	4.772
		Mean value of e = 4.775	

THE PRINCIPAL SERIES OF HELIUM

The two principal series of helium not only converge toward a different wave-length and central charge from the subordinate series, as does the principal series of hydrogen, but they converge toward different central charges in the two helium groups. Thus

the principal series of Group I converges toward a central charge $Q=2e\sqrt{\frac{1}{(1.69)^2}}$, and the principal series in the parhelium group converges toward a charge $Q=2e\sqrt{\frac{1}{(1.85)^2}}$. The principal series in hydrogen converges toward a charge $Q=2e\sqrt{\frac{1}{(1.5)^2}}$.

Both the principal series in helium seems to have the same value for $1/q^2$ in the Ritz equation. This value may be taken as $1/q^2=1/(m-.06)^2$. These values are only approximate, but are as close as are needed in calculating the value of e.

The principal series in the helium group gives the more consistent values of e, but with the exception of the first two lines of the parhelium series the values of e calculated from this series agree satisfactorily. The values of e as calculated from the different lines of these series are given in Tables V and VI.

TABLE V*

UNIT ELECTRICAL CHARGE FROM PRINCIPAL SERIES OF HELIUM, GROUP I

m	λ	Q	e
2	10830	2.77	4.776
3	3889	4.62	4.772
4	3188	5.10	4.770
5	2945	5.305	4.770
6	2829	5.415	4.775
7	2764	5.48	4.773
8	2723	5.52	4.775
9	2696	5.545	4.772
10	2677	5.560	4.768
11	2663	5.580	4.773
12	2657	5.594	4.772
13	2645	5.600	4.774
		Mean value of $e=4.7725$	

*The equation used in this computation is $Q=2e\sqrt{\frac{1}{(1.69)^2}-\frac{1}{(m-.06)^2}}$

TABLE VI*

UNIT ELECTRICAL CHARGE FROM PRINCIPAL SERIES OF PARHELIUM

m	λ	Q	e
3	5016	4.069	4.843
4	3965	4.577	4.795
5	3614	4.794	4.783
6	3448	4.908	4.778
7	3355	4.976	4.775
8	3297	5.019	4.772
9	3258	5.049	4.773
10	3231	5.070	4.774
11	3212	5.085	4.772
12	3197	5.097	4.772
13	3177	5.110	4.775
	Omitting the first two lines, $e = 4.775$		

* Calculated from the equation $Q = 2e\sqrt{\frac{1}{(1.85)^2} - \frac{1}{(m-.06)^2}}$

STANFORD UNIVERSITY
March 1919

PHOTO-ELECTRIC MEASURES OF THE LIGHT OF NOVA AQUILAE NO. 3

By JOEL STEBBINS and ELMER DERSHEM

We did not learn of the appearance of the Nova until the morning of June 9, when Mr. Stebbins at Rock Springs heard by telephone from Mr. Frost that a first-magnitude new star had been discovered by Mr. Barnard at Green River the previous night. A telegram was promptly sent to Urbana, and by special effort a photometric measure was secured on June 9. The night of June 8 had been clear throughout at Urbana, and a series of photo-electric observations of stars on the regular program was carried on until about fifteen hours local time. The observers then closed up the dome and walked away toward the northwest, missing the opportunity of measuring the Nova at the critical time. The disappointment of not seeing the Nova on the first night was compensated in part by the following ten nights being clear, but we shall always regret that some accident did not bring the Nova to our attention on June 8.

In its present condition the photo-electric photometer, attached to the 12-inch refractor, gives satisfactory measures of stars as faint as photographic magnitude 5.5. Although stars fainter than this can be observed, the measures become slow and burdensome because of the extra precautions necessary. We have tried objects as faint as magnitude 7.5 and got measurable effects, but there is no need of pushing things to the limit when there are so many brighter stars available. In the six months from June 9 to December 10 the Nova was well within the working range of the apparatus, and measures were secured on 79 nights, every clear night except two when the photometer was out of order. From June to the middle of September the observations were all made by Mr. Dershem, and after that time the work was divided between us. We are indebted to Miss Iva Hamlin for most of the reductions.

The magnitudes, which are derived with a potassium photo-electric cell, are very near to photographic magnitudes. The

color-equation of our apparatus is 0.86 magnitude; i.e., a star of spectrum Ko is measured 0.86 magnitude fainter than an Ao star of the same visual brightness.

The photo-electric measures are most satisfactory when the stars to be compared do not differ more than half a magnitude in brightness, and it is always aimed to choose stars as nearly equal as possible. However, as suitable comparison stars are often difficult to find, we have been using, for some time, a series of shade glasses to increase the working range of the instrument. These shades range in absorptive power from about half a magnitude to three magnitudes, and are all nearly neutral in tint. They were

TABLE I

ABSORPTION OF SHADE GLASSES

Star	Magnitude	Spectrum	I	II	III
ζ Persei	2.91	B1	$0^{M}.78$	$1^{M}.66$	$2^{M}.80$
γ Pegasi	2.87	B2	0.77	1.61	2.81
α Andromedae	2.15	Ao	0.79	1.65	2.81
α Aquilae	0.89	A5	0.80	1.72	2.85
δ Aquilae	3.44	Fo	0.79	.....	.....
α Persei	1.90	F5	0.83	1.76	2.84
γ Cygni	2.32	F8	0.84	1.80	2.85
α Cassiopeiae	2.47	Ko	0.84	1.81	2.79
α Arietis	2.23	K2	0.84	1.83	2.81
β Andromedae	2.37	Ma	0.86	1.86	2.80
β Pegasi	2.61	Mb	0.86	1.85	2.78

made from some plane dark spectacle glasses which we managed to gather up in war time. In comparing two stars of unequal brightness, one star of the two is always observed through the same shade, so that the effect of the shade need be known only approximately, since only variations of light are studied.

For the work on Nova it was necessary to know the absorption of each shade, and when we came to make tests we found marked differences for stars of various spectral types. In all strictness the absorption of each shade should be known for every wave-length, but for our purpose it is sufficient to measure the absorption under the working conditions of the instrument. In Table I are given the measures for the three shades, I, II, and III. The result for each star is the mean of four determinations, made on two or more nights.

Although ten stars are scarcely sufficient for a definitive measure, they indicate very well the differences of the shades for the spectral classes, but there are no doubt peculiarities of the individual stars. Since the tests were made we have learned from Mr. W. S. Adams that γ Cygni has a peculiar spectrum, which might have been suspected from the shade tests. In fact, by using strongly colored shades it would be quite feasible to work out a method of measuring quantitively the spectral class of a star. From smooth curves, drawn to represent the results in Table I, the values in Table II were derived.

TABLE II

ADOPTED VALUES OF SHADE GLASSES

Spectrum	I	II	III
Bo	$0^{M}77$	$1^{M}63$	$2^{M}80$
Ao	0.79	1.68	2.82
Fo	0.81	1.73	2.84
Go	0.82	1.78	2.84
Ko	0.84	1.82	2.82
Mo	0.86	1.86	2.79
Nova	0.79	1.68	2.82

It turns out that the difference of absorption between spectral classes B and M is $0^{M}09$ for shade I, and $0^{M}23$ for shade II, while for shade III the variation is smaller. These differences were not suspected at all when the observations of the Nova were being made, and it is necessary to know the equivalent spectrum of the Nova on any date in order to apply the proper shade correction. However, we were careful not to put in too many complications, and for the first month shade III was always used, followed by II, and then I as the star grew fainter. Rather than to attempt to bring the Nova into the spectral class of other stars we have uniformly used the shade values for class Ao for the Nova. This may introduce a variable systematic error, especially with shade II, as the Nova changed in spectrum, but the error will not be large, probably less than a tenth of a magnitude. When the Nova was observed both with and without a shade on the same night no great difference was noted.

In the matter of comparison stars, there was the choice of using only one or two objects, which would give the most accurate results,

provided the comparison stars themselves did not vary; or several stars could be included, each being used when the correction for atmospheric extinction was small. We chose to use several stars, since an unknown or irregular variation of a single comparison object might vitiate an entire series of measures.

In Table III are given the comparison stars, also their adopted "photo-electric" magnitudes, which were determined directly by suitable measures here. In order to compare these with visual magnitudes we may apply the correction in the fourth column, which is simply 0.86 times the color-index of the corresponding

TABLE III

COMPARISON STARS

Star	Photo-electric Magnitude	Spectrum	Color-Correction	Photo-electric Visual Magnitude	Harvard Visual Magnitude	H.—O.
α Aquilae	1.01	A5	+ $^{M}12$	0.89	0.89	$0^{M}00$
α Aquilae, II	2.73					
θ Aquilae	3.19	A0	.00	3.19	3.37	+ .18
δ Aquilae	3.64	F0	+ .24	3.40	3.44	+ .04
γ Aquilae	3.83	K2	+ .92	2.91	2.80	− .11
α Aquilae, III	3.84					
η Serpentis	4.03	K0	+ .86	3.17	3.42	+ .25
δ Aquilae, I	4.46					
4 Aquilae	5.04	B5	− .10	5.14	5.04	− .10
5 Aquilae	5.82	A0	.00	5.82	5.68	− .14

spectrum class, as given by Professor E. C. Pickering.[1] The resulting "photo-electric visual" magnitudes should be directly comparable with the Harvard visual magnitudes, and the differences are given in the last column.

The starting-point for the photo-electric magnitudes was fixed provisionally by adopting 1.01 for α Aquilae, which comes from the visual magnitude of 0.89. The systematic difference shown in the table is so small that we have let the magnitudes remain as they are.

In Table IV are our observations of the Nova. When a shade was used on Nova the correction is noted in the third column, a blank meaning no shade. In the fourth column each observation is usually the mean of three sets of measures, sometimes only two

[1] *Harvard Annals*, 80, 151, 1917.

TABLE IV

OBSERVATIONS OF NOVA AQUILAE NO. 3

Date	G.M.T.	Shade	Difference of Magnitude	Magnitude of Comparison Star	Magnitude of Nova	Remarks
1918 June 9...	18^h47^m	−2.82	−1.48	3.83	−0.47	¼ set, clear
	18 57	−2.82	−1.55	3.84	−0.53	½ set, between clouds
10...	16 39	−2.82	−0.81	4.03	+0.40	
	17 00	−2.82	−0.80	4.03	0.41	
	17 47	−2.82	−0.71	3.84	0.31	
	18 13	−2.82	−0.72	3.84	0.30	
	18 58	−2.82	−0.50	3.64	0.32	
	18 58	−2 82	−0.91	4.03	0.30	
	19 57	−2.82	−0.37	3.64	0.45	
	21 14	−2.82	+0.48	3.19	0.85	Nova fainter
11...	17 38	−2.82	−0.61	4.03	0.60	
	18 05	−2.82	−0.50	3.84	0.52	
	18 38	−2.82	−0.27	3.64	0.55	
	18 38	−2.82	−0.66	4.03	0.55	
	19 10	−2.82	−0.51	3.84	0.51	
	20 17	−2.82	+0.20	3.19	0.57	
	20 36	−2.82	+0.22	3.19	0.59	
12...	16 13	−2.82	−0.32	4.03	0.89	
	17 22	−2.82	−0.28	4.03	0.93	
	17 56	−2.82	−0.12	3.84	0.90	
	18 32	−2.82	+0.12	3.64	0.94	
	18 32	−2.82	−0.28	4.03	0.93	
	19 08	−2.82	−0.07	3.84	0.95	
	19 33	−2.82	+0.13	3.64	0.95	Very poor
	20 22	−2.82	+0.56	3.19	0.93	
	20 41	−2.82	+0.58	3.19	0.95	
13....	16 07	−2.82	−0.04	4.03	1.17	
	16 33	−2.82	+0.01	4.03	1.22	
	17 56	−2.82	+0.34	3.64	1.16	
	17 56	−2.82	−0.02	4.03	1.19	
	18 29	−2.82	+0.20	3.84	1.22	
	18 58	−2.82	+0.39	3.64	1.21	
	19 20	−2 82	+0.43	3.64	1.25	
	19 59	−2.82	+0.38	3.64	1.20	
	20 25	−2.82	+0.83	3.19	1.20	
14....	20 11	−2.82	+0.61	3.64	1.43	Poor sky, extinction 0.10
15....	16 13	−1.68	−0.67	4.03	1.68	Discordant, poor sky
	16 39	−1.68	−0.64	4.03	1.71	Discordant, poor sky
	17 59	−1.68	+0.60	2.73	1.65	Discordant, poor sky
	19 24	−1.68	−0.28	3.64	1.68	Discordant, poor sky
	19 51	−1.68	−0.29	3.64	1.67	Discordant, poor sky
	20 22	−1.68	+0.15	3.19	1.66	Discordant, poor sky
	20 49	−1.68	+0.11	3.19	1.62	Discordant, poor sky, extinction 0.10
16....	17 31	−1.68	−0.46	4.03	1.89	
	17 55	−1.68	+0.82	2.73	1.87	
	18 17	−1.68	+0.82	2.73	1.87	
	19 14	−1.68	−0.09	3.64	1.87	
	19 14	−1.68	−0.50	4.03	1.85	
	19 55	−1.68	−0.09	3.64	1.87	

TABLE IV—*Continued*

Date	G.M.T.	Shade	Difference of Magnitude	Magnitude of Comparison Star	Magnitude of Nova	Remarks
June 17....	16h15m	−1.68	−0.32	4.03	+2.03	
	17 11	−1.68	−0.36	4.03	1.99	
	17 29	−1.68	−0.33	4.03	2.02	1 set
	17 29	−1.68	+0.05	3.64	2.01	1 set
18....	16 30	−1.68	−0.27	4.03	2.08	
	16 52	−1.68	−0.30	4.03	2.05	
	17 47	−1.68	+1.04	2.73	2.09	
	19 22	−1.68	+0.02	3.64	1.98	½ set
	19 22	−1.68	−0.30	4.03	2.05	½ set
	20 10	−1.68	+0.08	3.64	2.04	
	20 33	−1.68	+0.55	3.19	2.06	
21....	19 03	−1.68	+0.28	4.03	2.63	Poor, smoke?
	19 28	−1.68	+0.63	3.64	2.59	Poor, smoke?
22....	17 16	−1.68	+0.48	4.03	2.83	½ set, worth something
23....	18 20	−0.79	−0.42	4.03	2.82	
	18 38	−0.79	−0.08	3.64	2.77	1 set
30....	15 38	.....	−0.65	4.03	3.38	
	17 15	.....	−0.73	4.03	3.30	
	17 42	.....	−0.35	3.64	3.29	
	19 37	−1.68	−0.02	5.04	3.34	
July 1....	15 45	.....	−0.81	4.03	3.22	
	16 09	.....	−0.85	4.03	3.18	1 set
	17 11	.....	−0.42	3.64	3.22	
	18 26	.....	−0.41	3.64	3.23	
	19 54	−1.68	−0.20	5.04	3.16	
3....	16 57	−0.79	−0.25	4.03	2.99	
	17 29	−0.79	+0.12	3.64	2.97	
	18 57	−1.68	−0.38	5.04	2.98	
5....	16 53	−0.79	−0.02	4.03	3.22	
	17 26	−0.79	+0.39	3.64	3.24	
8....	15 23	−0.79	+0.26	4.03	3.50	
	16 24	−0.79	+0.23	4.03	3.47	
	17 50	.....	−0.11	3.64	3.53	
10....	15 54	.....	−0.17	4.03	3.86	
	17 43	.....	+0.22	3.64	3.86	
	19 19	−0.79	−0.39	5.04	3.86	
11....	15 51	.....	−0.20	4.03	3.83	
	17 21	.....	+0.20	3.64	3.84	
	17 55	−0.79	−0.40	5.04	3.85	
	19 17	−0.79	−0.41	5.04	3.84	Very poor, smoke
12....	15 52	.....	−0.08	4.03	3.95	
	16 44	.....	+0.23	3.64	3.87	
	17 35	−0.79	−0.36	5.04	3.89	
	19 36	−0.79	−0.36	5.04	3.89	
18....	15 06	−0.79	+0.48	4.03	3.72	
	16 58	.....	+0.08	3.64	3.72	
	17 57	−0.79	−0.57	5.04	3.68	
	19 22	−0.79	−0.56	5.04	3.69	
19....	14 58	.....	−0.15	4.03	3.88	
	16 24	.....	+0.18	3.64	3.82	
	17 24	−0.79	−0.40	5.04	3.85	

TABLE IV—*Continued*

Date	G.M.T.	Shade	Difference of Magnitude	Magnitude of Comparison Star	Magnitude of Nova	Remarks
July 20....	15^h21^m	.....	+0.08	4.03	4.11	
	16 37	.....	+0.38	3.64	4.02	
22....	14 54	.....	+0.22	4.03	4.25	Moon
27....	14 55	.....	−0.32	4.03	3.71	
	16 08	.....	+0.04	3.64	3.68	
	17 06	−0.79	−0.56	5.04	3.69	
	18 16	−0.79	−0.55	5.04	3.70	
29....	15 32	.....	−0.17	4.03	3.86	
	15 56	.....	+0.20	3.64	3.84	
	16 15	.....	+0.24	3.64	3.88	
	17 17	−0.79	−0.38	5.04	3.87	
30....	14 41	.....	−0.14	4.03	3.89	
	15 53	.....	+0.26	3.64	3.90	
	17 11	−0.79	−0.35	5.04	3.90	
31....	14 38	.....	−0.02	4.03	4.01	
	15 47	.....	+0.37	3.64	4.01	
	16 40	−0.79	−0.20	5.04	4.05	
	18 26	−0.79	−0.17	5.04	4.08	
Aug. 1....	15 40	.....	+0.84	3.64	4.48	
	16 07	.....	+0.01	4.46	4.47	Poor
	16 42	−0.79	+0.26	5.04	4.51	
	17 01	−0.79	+0.23	5.04	4.48	
	18 13	−0.79	+0.24	5.04	4.49	
3....	14 51	.....	+0.48	4.03	4.51	
	15 49	.....	+0.08	4.46	4.54	
	17 22	−0.79	+0.30	5.04	4.55	1 set
4....	14 55	.....	+0.45	4.03	4.48	Poor sky
	15 22	.....	−0.09	4.46	4.37	Poor sky
	15 42	.....	+0.03	4.46	4.49	Poor sky
5....	15 40	.....	+0.16	4.46	4.62	
	17 20	.....	−0.48	5.04	4.56	
6....	14 42	.....	−0.14	4.03	3.89	
	15 28	.....	−0.60	4.46	3.86	Very poor sky
7....	14 52	.....	−0.28	4.03	3.75	
	15 45	.....	−0.75	4.46	3.71	1 set
	15 52	.....	+0.10	3.64	3.74	
	16 45	−0.79	−0.48	5.04	3.77	
	18 09	−0.79	−0.48	5.04	3.77	Poor
9....	14 55	.....	+0.02	4.03	4.05	
	15 20	.....	+0.43	3.64	4.07	
	15 36	.....	+0.38	3.64	4.02	
11....	14 39	.....	+0.05	4.03	4.08	
	15 06	.....	+0.43	3.64	4.07	
	15 30	.....	+0.44	3.64	4.08	
	17 04	−0.79	−0.13	5.04	4.12	
12....	14 51	.....	+0.37	4.03	4.40	
	15 20	.....	−0.15	4.46	4.31	δ Aquilae faint
	15 43	.....	−0.14	4.46	4.32	
	17 00	−0.79	+0.17	5.04	4.42	
14....	14 56	.....	−0.04	4.46	4.42	
	15 24	.....	−0.09	4.46	4.37	

TABLE IV—*Continued*

Date	G.M.T.	Shade	Difference of Magnitude	Magnitude of Comparison Star	Magnitude of Nova	Remarks
Aug. 21....	14^h24^m	.....	0.00	4.46	4.46	Moon } δ faint
	14 48	.....	+0.01	4.46	4.47	Moon }
	16 22	−0.79	+0.26	5.04	4.51	Moon
22....	14 15	.....	+0.51	4.03	4.54	Moon
	14 45	.....	0.00	4.46	4.46	Moon } δ faint
	15 07	.....	0.00	4.46	4.46	Moon }
	16 30	−0.79	+0.31	5.04	4.56	Moon
31....	14 17	.....	+0.45	4.46	4.91	
	16 25	.....	−0.12	5.04	4.92	
Sept. 1....	14 06	.....	+0.47	4.46	4.93	
	14 36	.....	−0.09	5.04	4.95	
5....	14 39	.....	+0.03	4.46	4.49	
	15 19	.....	−0.52	5.04	4.52	
6....	14 14	.....	−0.08	4.46	4.38	
8....	14 12	.....	+0.27	4.46	4.73	
	15 11	.....	−0.32	5.04	4.72	
16....	13 49	.....	−0.07	5.04	4.97	
	14 17	.....	−0.06	5.04	4.98	
19....	14 23	.....	−0.07	5.04	4.97 }	Nova changed
	14 40	.....	−0.14	5.04	4.90 }	
21....	14 48	.....	−0.27	5.04	4.77	
	15 13	.....	−0.30	5.04	4.74	
22....	14 42	.....	−0.13	5.04	4.91	
	15 03	.....	−0.12	5.04	4.92	
26....	13 53	.....	+0.04	5.04	5.08	
27....	14 48	.....	−0.06	5.04	4.98	
28....	14 21	.....	−0.04	5.04	5.00	
	14 42	.....	−0.03	5.04	5.01	
29....	13 33	.....	+0.04	5.04	5.08	
	13 52	.....	+0.02	5.04	5.06	
Oct. 3....	13 20	.....	+0.03	5.04	5.07	
	13 40	.....	+0.03	5.04	5.07	
5....	14 33	.....	+0.06	5.04	5.10	
6....	13 08	.....	+0.08	5.04	5.12	
	13 34	.....	+0.09	5.04	5.13	
12....	12 54	.....	−0.23	5.04	4.81	
	13 15	.....	−0.20	5.04	4.84	
14....	13 23	.....	+0.24	5.04	5.28	
	13 47	.....	+0.24	5.04	5.28	
15....	12 38	.....	+0.26	5.04	5.30	Poor sky
16....	12 55	.....	+0.24	5.04	5.28	Poor sky
	13 20	.....	+0.25	5.04	5.29	Poor sky
20....	12 43	.....	+0.16	5.04	5.20	
	13 01	.....	+0.15	5.04	5.19	
21....	12 27	.....	+0.27	5.04	5.31	
	12 48	.....	+0.27	5.04	5.31	
27....	12 28	.....	+0.36	5.04	5.40	
	12 56	.....	+0.35	5.04	5.39	
28....	12 29	.....	+0.34	5.04	5.38	
29....	12 11	.....	+0.35	5.04	5.39	
	12 36	.....	+0.36	5.04	5.40	

TABLE IV—*Continued*

Date	G.M.T.	Shade	Difference of Magnitude	Magnitude of Comparison Star	Magnitude of Nova	Remarks
Nov. 1....	12^h52^m	.....	+0.17	5.04	5.21	
	13 09	.....	+0.18	5.04	5.22	
2....	12 07	.....	+0.35	5.04	5.39	
	12 30	.....	+0.33	5.04	5.37	
Nov. 4....	12 51	.....	+0.37	5.04	5.41	Smoke
5....	12 47	.....	+0.39	5.04	5.43	
	12 47	.....	−0.40	5.82	5.42	
10....	12 33	.....	+0.40	5.04	5.44	
	12 33	.....	−0.32	5.82	5.50	
11....	12 09	.....	+0.44	5.04	5.48	
	12 09	.....	−0.39	5.82	5.43	
12....	12 01	.....	+0.44	5.04	5.48	Smoke
	12 01	.....	−0.43	5.82	5.39	
12....	11 57	.....	+0.40	5.04	5.44	
	11 57	.....	−0.44	5.82	5.38	
24....	12 00	.....	−0.18	5.82	5.64	1 set
	12 06	.....	+0.54	5.04	5.58	
29....	11 39	.....	−0.30	5.82	5.52	1 set
	11 42	.....	+0.51	5.04	5.55	
30....	11 48	.....	+0.54	5.04	5.58	
Dec. 10....	11 36	.....	+0.63	5.04	5.67	Twilight

sets, but if less than two that fact is noted in the remarks. A set of measures normally includes two readings on the comparison star, four on the Nova, and then two on the comparison star again. Three sets may be secured in as short a time as fifteen minutes, but half an hour is a better average for all conditions. A half-set would mean that for some reason, usually because clouds came suddenly, the second pair of readings on the comparison star was not secured. It is our usual practice to reject all incomplete measures of this sort, but where the choice is between a perfect set or nothing at all we must take what we can get. The comparison star used is identified by its magnitude given in the fifth column. Each adopted magnitude of the Nova, as given in the sixth column, was obtained by adding the corresponding numbers in the three preceding columns.

An observation was marked poor when the readings of a set were discordant, which was usually due to a passing cloud or smoke. When the sky was called poor it was "thick" but apparently uniform, for only under extraordinary circumstances would measures

be undertaken with an uneven sky. We observed the Nova on many occasions when conditions were unfit for our regular program, but it was felt that the results would be of value even with errors of several hundredths of a magnitude. The effect of the sky background at the time of full moon is usually negligible, as the light from a star passes through a diaphragm which has a field of only 2′.4 diameter. However, when faint stars are compared and a shade is used for only one of them, the moon effect may be troublesome to determine, and these cases are noted in the remarks.

All of the measures have been corrected for atmospheric extinction, but in four-fifths of the cases this correction was less than $0^{M}.03$, and only twice did it exceed $0^{M}.07$, these occasions being noted in the remarks.

The accordance of the measures is shown by the residuals given by the several sets in each observation, from which we find,

$$\text{Probable error of one observation} = \pm 0^{M}.009$$

This includes only the accidental errors at the time of the measures, and it is better to compute the probable error from the residuals formed by comparing each result in Table IV with the mean for the corresponding night. Using all measures after June 11 we find,

$$\text{Probable error of one observation} = \pm 0^{M}.019$$

Included in this probable error are all poor and incomplete measures, all outstanding errors in the values for the shade glasses and in the magnitudes of the comparison stars, and all variations of light of the Nova and of the comparison stars. Both of the foregoing values of the probable error are larger than would be tolerated in regular work with this photometer, but the accuracy is quite sufficient to follow the changes of the Nova.

Our measures of Nova Aquilae were undertaken to detect any rapid changes of light, such as are sometimes reported in the case of a new star. In this we were quite disappointed, for although the measures often extended over four or five hours there was only one night, June 10, when a variation as large as 0.10 magnitude could be established. On other dates there were suspicions of

progressive changes which will probably fit in with the course of the general light-curve of the Nova, but so far as these measures are concerned we may dismiss any notion of sudden and erratic variations in the course of an hour or so.

The measures on June 9 call perhaps for special mention, as there is some doubt from the estimates of visual observers as to how bright the Nova really became. Watch was kept here during most of that night, but it was only once when the sky cleared for a few minutes that some readings could be taken. Although we should have been glad to have had more measures, the resulting magnitude, -0.50, can scarcely be in error as much as a tenth of a magnitude. This photo-electric result cannot be reconciled with visual estimates of -1.0 magnitude or brighter, as the Nova was not a red star on that date.

In photometric observations it is always proper to suspect every comparison star of light-variation, and the measures in Table IV furnish good tests of the constancy of the various stars observed. The only star that we suspect strongly is δ Aquilae, which apparently was about a tenth of a magnitude faint on one or two nights, particularly on August 12. We do not overlook the fact that finger marks or a film of moisture on the shade glass would have produced just the same effect, but it is our practice to wipe off and examine both sides of a shade *every* time that it is used. It is therefore highly improbable that a dirty shade glass was the cause of these discordances.

Although we managed to observe the Nova on nearly half the nights during six months, the series is not extended enough to make a separate study of the light-curve, but it is probable that the magnitudes given will conform nearly with the visual scale, so that no great difficulty will be found in using these measures in the general discussion of the light-changes.

The development of the photo-electric photometer has been in collaboration with Dr. Jakob Kunz, and the work described in this paper is a part of that carried on with the aid of a grant from the Draper Fund of the National Academy of Sciences.

UNIVERSITY OF ILLINOIS OBSERVATORY
February 1919

Reviews

A Treatise on the Sun's Radiation and Other Solar Phenomena. By FRANK H. BIGELOW. New York: John Wiley & Sons, Inc., 1918. Figs. 44. 8vo, pp. ix+385. $5.00.

This book contains an account of the further developments of the thermodynamical theory of radiation which was described in the author's *Atmospheric Circulation and Radiation.*

It is well known that when an atmosphere is treated as an ideal gas stratified in such a way that there is indifferent or adiabatic equilibrium, the temperature-gradient is determined by the equation

$$C_p dT = -g dz, \tag{1}$$

where C_p is the specific heat at constant pressure, T the temperature, z the altitude, and g the acceleration of gravity. In the usual deduction[1] of this equation use is made of the equations

$$Pv = RT, \qquad C_p - C_v = R, \tag{2}$$

which are characteristic of an ideal gas.

Recognizing that actual temperature-gradients are often different from the adiabatic, Professor Bigelow proposes a non-adiabatic scheme of equations exactly like the foregoing except that C_p, C_v, and R are treated as quantities which vary with the altitude. The quantities C_p, C_v thus defined are still called specific heats, but it is not evident that this is justifiable, since the usual proof of equation (1) breaks down when the temperature-gradient is not adiabatic. If I understand the author correctly, he assumes that in a thermodynamical change, which takes place without a change in altitude, the variations in specific volume, v, pressure, P, and temperature, T, are connected by the relation

$$Pdv + vdP = RdT,$$

but that when in addition there is a change in altitude the corresponding relation should be

$$Pdv + vdP = RdT + TdR.$$

[1] Cf. W. J. Humphreys, "The Physics of the Air," *Journal of the Franklin Institute*, **184**, 161, 1917.

The variation of R with altitude is attributed to changes in composition and motion of the atmosphere, to gravitation, to the emission and absorption of radiant heat, and perhaps also to the density and pressure of radiation. When the conditions are such that $dR=0$ the temperature-gradient is adiabatic.

It should be noticed that if, on the other hand, R is regarded as a function of P and v in the equation of state $Pv=RT$, the well-known equation[1]

$$C_p-C_v=T\left(\frac{\delta v}{\delta T}\right)_p\left(\frac{\delta P}{\delta T}\right)_v, \tag{3}$$

which is valid for any substance, gives, when combined with $C_p-C_v=R$, the following partial differential equation for R:

$$vR\frac{\delta R}{\delta v}+PR\frac{\delta R}{\delta P}=Pv\frac{\delta R}{\delta v}\frac{\delta R}{\delta P} \tag{4}$$

This equation evidently restricts the form of the equation of state. A complete integral is

$$R=cv^aP^b, \tag{5}$$

where a, b, and c are constants connected by the relation $ab=a+b$. Thus a possible equation of state is

$$P^xv^{\frac{x}{x-1}}=cT, \tag{6}$$

where x and c are constants, and a more general equation compatible with the foregoing conditions may be obtained by the method of generalization employed in the theory of partial differential equations.

The foregoing relation is not inconsistent with Mr. Bigelow's fundamental relations

$$\frac{P_1}{P_0}=\left(\frac{T_1}{T_0}\right)^{\frac{nk}{k-1}}, \qquad \frac{\rho_1}{\rho_0}=\left(\frac{T_1}{T_0}\right)^{\frac{n}{k-1}}, \tag{7}$$

which connect the pressures, temperatures, and densities at the top and bottom of a layer, for k is a constant, and n, the ratio of the adiabatic temperature-gradient to the actual gradient, is treated as practically constant within a layer, a mean value being actually used.

It should be mentioned that the equation $C_p-C_v=R$ is apparently simply a hypothesis. If, moreover, C_p is regarded as an adiabatic

[1] Cf. W. C. McC. Lewis, *Physical Chemistry*, 2, 74, 1916.

invariant defined by equation (1), and C_v as a second adiabatic invariant defined by the equations (2), it would seem that Bigelow's theory is essentially a development of the hypothesis that the ratio $\frac{C_p}{C_v}=K$ is constant, i.e., the same at all levels. This hypothesis is made, however, with some reservation, for in the computations it is found necessary to treat hydrogen as monatomic with $K=\frac{5}{3}$ below a certain level, but as diatomic H_2 with $K=\frac{7}{5}$ above that level.

Computations are made in which the solar atmosphere is treated successively as consisting entirely of H_1, H_2, He, C, Ca, Zn, Cd, and Hg respectively. The partial pressures of the different substances in the actual solar atmosphere can of course be obtained from the total pressure, P, when the total amounts of the different substances are known.

A reference plane of thermal equilibrium at some unknown level in the sun is derived from the terrestrial data by multiplying P, v, T, R, C_p, and C_v by the factor $\gamma=28.028$, which is the ratio of the accelerations of gravity on the sun and the earth. The level of this reference plane ($P=28.028$ atmospheres) occurs at very different distances below the photosphere ($P=6$) for the different gases but is in each case in the isothermal region, which extends upward beyond the level of the photosphere and changes gradually into another non-adiabatic region, in which the temperature, pressure, and R decrease with the altitude down to zero values. Below the isothermal region there is an adiabatic region. The depth of the isothermal region is great for the light gases and small for the heavy ones. The temperature is estimated at 7686°.7 absolute, being nearly the same for all the gases. The level $P=6$ is also found to be the same for all.

Another interesting conclusion is that the sun's disk is not an optical effect but the vanishing level of the heavy metallic vapors under the operation of the prevailing thermodynamic conditions. The computations show in fact that the pressures of Hg, Cd, and Zn fall to zero at a comparatively small distance above the photosphere. The element Ca just floats comfortably upon the layers of the still heavier gases, and it is easily observed in the spectroheliograph as a surface phenomenon, having many configurations as in the faculae and flocculi. The lighter gases, especially He and H, rise to great heights, the H to the top of the inner corona. It is claimed that the distributions indicated by the computations conform well with the results of the spectroheliographic observations upon the heights of the chemical elements in the sun.

The author next attacks the problem of the solar radiation, basing his computations on the following expression for the mean value within a layer of the specific intensity of radiation:

$$K_{10} \equiv cT^a = \frac{U_1 - U_0}{v_1 - v_0}, \tag{8}$$

where U_1, U_0; v_1, v_0 are the values of the inner energy and specific volume respectively at the two boundaries of the layer. The quantities U_1 and U_0 are assumed to be connected by the relation

$$U_1 - U_0 = (C_{p_a} - R_{10})(T_a - T_0),$$

which is an "adaptation" of the thermodynamical relation which holds in the adiabatic case. As the derivation of this formula is not explained I cannot quite make out whether or not it involves the assumption that the non-adiabatic C_p and C_v are actually specific heats. The computations lead to some interesting conclusions. They indicate that the factor c in the formula (8) suffers a very large change in value in passing from the isothermal region to the adiabatic, while the exponent a changes from 4 to 2.4. It is concluded from this that the solar radiation originates in a saltum process at the bottom of the isothermal layer and continues throughout the isothermal region as black radiation, a result which is thought to be in agreement with Emden's conclusion that an isothermal atmosphere of sufficient thickness emits black radiation. It is found, moreover, that the gradient of the heat content does not change suddenly, and so it is concluded that radiation is not a common thermodynamic process, as Planck assumes. A theory of radiation is then developed and compared with those of Planck and Bohr.

The book is frankly revolutionary and challenges the results of previous investigators. Perhaps the most serious objections to the theory are that the number of assumptions seems to be large, and that many quantities which in everyday physics are reverently treated as constants are here regarded as variables. Among these we may mention the number of molecules per unit mass and the constant k in the Boltzmann-Planck relation between entropy and probability. This last assumption is in direct contradiction with the statement in Planck's *Theory of Heat Radiation* (translation by Masius, p. 119) that k is a universal constant, the same for a terrestrial as for a cosmic system. It should be mentioned, however, that according to P. Ehrenfest (*Phil. Mag.*, **33**, 500, 1917) the relation $S = k \log W$ between entropy and

probability has not been definitely proved and has been regarded in recent years simply as a postulate. Bigelow's hypothesis of a variable k may then be quite defensible.

As a work of imagination the book may be compared with Planck's *Theorie der Wärmestrahlung*, for it is a really remarkable attempt to develop a type of mathematical analysis which is capable of accounting for the complex conditions which obtain in the solar atmosphere. Just as in the case of Planck's theory there are many things which are hard to understand from a strictly logical point of view, but Planck's theory has been of undoubted value in the development of mathematical physics, and so it would be unwise to reject the present theory on account of these difficulties. As to the validity of the conclusions time must decide.

H. BATEMAN

THROOP COLLEGE OF TECHNOLOGY, PASADENA, CAL.
February 27, 1919

Mirrors, Prisms and Lenses, a Text-book of Geometrical Optics. By JAMES P. C. SOUTHALL. New York: Macmillan, 1918. Pp. xix+579, Figs. 247. $3.25.

This book by Professor Southall ought to receive a wide welcome. The war has brought out too distinctly the error made by the English-speaking people in neglecting the optician's art, a neglect even more marked in this country than in England. It is to be hoped that this volume may do much to reduce this fault in the future.

The book has fifteen chapters, of which the first three deal with the elementary phenomena of optics. The following chapters, up to the last, give descriptions of the principal systems, with clear expositions of their elementary theories and of the principles of their actions. An admirable feature of the book is the collection of numerous problems at the ends of the chapters, which should yield a conscientious student a great deal of accurate and available knowledge when he shall have solved them.

The last chapter, which may be regarded as necessary for a complete view of the optical art, is hardly simple enough to attach logically to the book up to that point.

Singularly few important errors betray themselves to the reader, while such as were noticed would afford valuable exercise to the student in detection and emendation.

One feature of the presentation of the subject might be worthy of passing comment. Since it is practically impossible either to construct an optical system or to determine its physical constants after construction to a degree of precision greatly in excess of one part in one thousand, it seems unfortunate to suggest to the student that seven-place logarithms are a proper auxiliary to his work. The labor of practical application of the theory to the solution of problems of construction is sufficiently formidable without the drudgery of unnecessary labor of computations.

C. S. HASTINGS

YALE UNIVERSITY, NEW HAVEN
February 25, 1919

A CORRECTION

The following correction should be made in the article "On the Dark Markings of the Sky" in the number of the *Astrophysical Journal* for January, **49**, 1, 1919. In the last paragraph on page 4

for No. 160, in $\alpha = 21^h34^m47^s$, $\delta = +55°41'$

read No. 150, in $\alpha = 20^h47^m47^s$, $\delta = +59°50'$. The rest of the paragraph is correct.

On the same page, second paragraph: the dark object (No. 15) in $\alpha = 4^h22^m50^s$, $\delta = +46°21'$ is really in a dark part of the Milky Way.

E. E. BARNARD

May 8, 1919

INDEX TO VOLUME XLIX

SUBJECTS

PAGE

Aerial Photometry. *M. Luckiesh* 108
Aquilae No. 3, Photo-Electric Measures of the Light of Nova. *Joel Stebbins* and *Elmer Dershem* 344
Aquilae No. 3 of 1918, Some Peculiarities of Nova. *E. E. Barnard* . . 199
Arc Spectra of Cobalt, Nickel, Manganese, and Chromium, The Infra-Red *H. M. Randall* and *E. F. Barker* 54
Arc Spectrum of Iron, The Infra-Red. *H. M. Randall* and *E. F. Barker* 42
Atomic Numbers of the Elements, Spectra and. *J. E. Paulson* . . . 276
Aurora Line, On the General Auroral Illumination of the Sky, and the Wave-Length of the Chief. *V. M. Slipher* 266
Brightness of the Corona at the Eclipse of June 8, 1918, A Photo-Electric Determination of the. *Jacob Kunz* and *Joel Stebbins* . 137
Catalogue of 182 Such Objects. On the Dark Markings of the Sky. *E. E. Barnard* (*See also* Correction, p. 360) 1
Cepheid Variation, Three Notes on. Ninth Paper. *Harlow Shapley* . 24
Chromium, The Infra-Red Arc Spectrum of. *H. M. Randall* and *E. F. Barker* 54
Clusters, Studies Based on the Colors and Magnitudes in Stellar.
  Ninth Paper: Three Notes on Cepheid Variation. *Harlow Shapley* 24
  Tenth Paper: A Critical Magnitude in the Sequence of Stellar Luminosities. *Harlow Shapley* 96
  Eleventh Paper: A Comparison of the Distances of Various Celestial Objects. *Harlow Shapley* 249
  Twelfth Paper: Remarks on the Arrangement of the Sidereal Universe. *Harlow Shapley* 311
Cobalt, The Infra-Red Arc Spectrum of. *H. M. Randall* and *E. F. Barker* 54
Color-Scales of One and of Two Dimensions, Correlation between the. *J. G. Hagen* 282
Color-Sensitiveness of Photo-Electric Cells. *T. Shinomiya* 303
Comet Mellish (1915*a*), Spectrum of. *A. Estelle Glancy* 196
Corona at the Eclipse of June 8, 1918, A Photo-Electric Determination of the Brightness of the. *Jacob Kunz* and *Joel Stebbins* 137
Correction to the Paper "On the Dark Markings of the Sky." *E. E. Barnard* 360

PAGE

Dark Markings of the Sky. With a Catalogue of 182 Such Objects. *E. E. Barnard* (*See also* Correction, p. 360) 1

Distances of Various Celestial Objects, A Comparison of the. Eleventh Paper. *Harlow Shapley* 249

Eclipse of June 8, 1918, A Photo-Electric Determination of the Brightness of the Corona at the. *Jacob Kunz* and *Joel Stebbins* . . 137

Electrical Charge, The Helium Spectrum and the Unit. *Fernando Sanford* 337

Elements, Spectra and Atomic Numbers of the. *J. E. Paulson* . . . 276

Furnace, Discussion of Some Evidence on the Origin of Radiation in the Tube-Resistance. *Arthur S. King* 48

Gratings, Theory of Imperfect. *C. M. Sparrow* 65

Helium Spectrum and the Unit Electrical Charge. *Fernando Sanford* . 337

Infra-Red Arc Spectra of Cobalt, Nickel, Manganese, and Chromium. *H. M. Randall* and *E. F. Barker* 54

Infra-Red Arc Spectrum of Iron. *H. M. Randall* and *E. F. Barker* . . 42

Iron, The Infra-Red Arc Spectrum of. *H. M. Randall* and *E. F. Barker* 42

Light of Nova Aquilae No. 3, Photo-Electric Measures of the. *Joel Stebbins* and *Elmer Dershem* 344

Line, On the General Auroral Illumination of the Sky, and the Wave-Length of the Chief Aurora. *V. M. Slipher* 266

Lines, Star with Disappearing Bright. *Edwin B. Frost* 61

Luminosities, A Critical Magnitude in the Sequence of Stellar. Tenth Paper. *Harlow Shapley* 96

Magnetic Polarity of Sun-Spots. *George E. Hale, Ferdinand Ellerman, S. B. Nicholson*, and *A. H. Joy* 153

Magnitude of the Stars, On the Use of Grating Spectra for Determining Spectral Type and Absolute. *Bertil Lindblad* 289

Magnitudes in Stellar Clusters, Studies Based on the Colors and. . .

Ninth Paper: Three Notes on Cepheid Variation. *Harlow Shapley* 24

Tenth Paper: A Critical Magnitude in the Sequence of Stellar Luminosities. *Harlow Shapley* 96

Eleventh Paper: A Comparison of the Distances of Various Celestial Objects. *Harlow Shapley* 249

Twelfth Paper: Remarks on the Arrangement of the Sidereal Universe. *Harlow Shapley* 311

Manganese, The Infra-Red Arc Spectrum of. *H. M. Randall* and *E. F. Barker* 54

Markings of the Sky, Dark. With a Catalogue of 182 Such Objects. *E. E. Barnard* (*See also* Correction, p. 360) 1

Mellish (1915*a*), Spectrum of Comet. *A. Estelle Glancy* 196

Motions in Space of Some Stars of High Radial Velocity. *Walter S. Adams* and *Alfred H. Joy* 179

PAGE

Nickel, The Infra-Red Arc Spectrum of. *H. M. Randall* and *E. F. Barker* 54
Notice to Authors and Subscribers 207
Nova Aquilae No. 3, Photo-Electric Measures of the Light of. *Joel Stebbins* and *Elmer Dershem* 344
Nova Aquilae No. 3 of 1918, Some Peculiarities of. *E. E. Barnard* . . 199
Orbits of Three Spectroscopic Binaries. *Walter S. Adams* and *Alfred H. Joy* 186
Photo-Electric Cells, Color-Sensitiveness of. *T. Shinomiya* 303
Photo-Electric Determination of the Brightness of the Corona at the Eclipse of June 8, 1918. *Jacob Kunz* and *Joel Stebbins* . . . 137
Photo-Electric Measures of the Light of Nova Aquilae No. 3. *Joel Stebbins* and *Elmer Dershem* 344
Photographic Plate Analogous to the Purkinje Effect, A Property of the. *J. A. Parkhurst* 202
Photometry, Aerial. *M. Luckiesh* 108
Pickering, Edward Charles, Notice of Death of 136
Polarity of Sun-Spots, The Magnetic. *George E. Hale, Ferdinand Ellerman, S. B. Nicholson,* and *A. H. Joy* 153
Purkinje Effect, A Property of the Photographic Plate Analogous to the. *J. A. Parkhurst* 202
Pyrometry, Monochromatic and Neutral-Tint Screens in Optical. *W. E. Forsythe* 237
Radial Velocity, Motions in Space of Some Stars of High. *Walter S. Adams* and *Alfred H. Joy* 179
Radiation in the Tube-Resistance Furnace, Discussion of Some Evidence on the Origin of. *Arthur S. King* 48
Reviews:
  Aitken, Robert Grant. *The Binary Stars* (G. Van Biesbroeck) . . 131
  Bigelow, Frank H. *A Treatise on the Sun's Radiation and Other Solar Phenomena* (H. Bateman) 355
  Müller, G., and E. Hartwig. *Geschichte und Literatur der veränderlichen Sterne.* Band I. (J. A. Parkhurst) 286
  Southall, James P. C. *Mirrors, Prisms and Lenses* (C. S. Hastings) 359
  Wigmore, John H., *Editor-in-Chief. Science and Learning in France, with a Survey of Opportunities for American Students in French Universities: an Appreciation by American Scholars* (Edwin B. Frost) 63
Screens in Optical Pyrometry, Monochromatic and Neutral-Tint. *W. E. Forsythe* 237
Sky, On the General Auroral Illumination of the, and the Wave-Length of the Chief Aurora Line. *V. M. Slipher* 266
Spectra and Atomic Numbers of the Elements. *J. E. Paulson* . . . 276

PAGE

Spectra for Determining Spectral Type and Absolute Magnitude of the Stars, On the Use of Grating. *Bertil Lindblad* 289
Spectra of Cobalt, Nickel, Manganese, and Chromium, The Infra-Red Arc. *H. M. Randall* and *E. F. Barker* 54
Spectra Produced in High Vacua. A Further Study of Metallic. *Edna Carter* and *Arthur S. King* 224
Spectral Type and Absolute Magnitude of the Stars, On the Use of Grating Spectra for Determining the. *Bertil Lindblad* . . . 289
Spectrograph of the 72-Inch Reflecting Telescope, The Stellar. *J. S. Plaskett* 209
Spectroscopic Binaries, Orbits of Three. *Walter S. Adams* and *Alfred H. Joy* 186
Spectrum and the Unit Electrical Charge, The Helium. *Fernando Sanford* 337
Spectrum of Comet Mellish (1915*a*). *A. Estelle Glancy* 196
Spectrum of Iron, the Infra-Red Arc. *H. M. Randall* and *E. F. Barker* 42
Star with Disappearing Bright Lines. *Edwin B. Frost* 61
Stars, On the Use of Grating Spectra for Determining Spectral Type and Absolute Magnitude of the. *Bertil Lindblad* 289
Stars of High Radial Velocity, Motions in Space of Some. *Walter S. Adams* and *Alfred H. Joy* 179
Stellar Clusters, Studies Based on the Colors and Magnitudes in.
  Ninth Paper: Three Notes on Cepheid Variation. *Harlow Shapley* 24
  Tenth Paper: A Critical Magnitude in the Sequence of Stellar Luminosities. *Harlow Shapley* 96
  Eleventh Paper: A Comparison of the Distances of Various Celestial Objects. *Harlow Shapley* 249
  Twelfth Paper: Remarks on the Arrangement of the Sidereal Universe. *Harlow Shapley* 311
Stellar Luminosities, A Critical Magnitude in the Sequence of.
  Tenth Paper. *Harlow Shapley* 96
Studies Based on the Colors and Magnitudes in Stellar Clusters.
  Ninth Paper: Three Notes on Cepheid Variation. *Harlow Shapley* 24
  Tenth Paper: A Critical Magnitude in the Sequence of Stellar Luminosities. *Harlow Shapley* 96
  Eleventh Paper: A Comparison of the Distances of Various Celestial Objects. *Harlow Shapley* 249
  Twelfth Paper: Remarks on the Arrangement of the Sidereal Universe. *Harlow Shapley* 311
Sun-Spots, The Magnetic Polarity of. *George E. Hale, Ferdinand Ellerman, S. B. Nicholson,* and *A. H. Joy* 153
Telescope, The Stellar Spectrograph of the 72-Inch Reflecting. *J. S. Plaskett* 209

PAGE

Type and Absolute Magnitude of the Stars, On the Use of Grating Spectra for Determining the Spectral. *Bertil Lindblad* 289

Universe, Remarks on the Arrangement of the Sidereal. Twelfth Paper. *Harlow Shapley* 311

Vacua, A Further Study of Metallic Spectra Produced in High. *Edna Carter* and *Arthur S. King* 224

Variation, Three Notes on Cepheid. Ninth Paper. *Harlow Shapley* . 24

Velocity, Motions in Space of Some Stars of High Radial. *Walter S. Adams* and *Alfred H. Joy* 179

Wave-Length of the Chief Aurora Line, On the General Auroral Illumination of the Sky and the. *V. M. Slipher* 266

INDEX TO VOLUME XLIX

AUTHORS

PAGE

ADAMS, WALTER S., and ALFRED H. JOY. The Motions in Space of Some Stars of High Radial Velocity 179
The Orbits of Three Spectroscopic Binaries 186
BARNARD, E. E. On the Dark Markings of the Sky. With a Catalogue of 182 Such Objects (*see also* Correction, p 360) 1
A Correction to the Paper "On the Dark Markings of the Sky" . 360
Some Peculiarities of Nova Aquilae III of 1918 199
BARKER, E. F., and H. M. Randall. The Infra-Red Arc Spectra of Cobalt, Nickel, Manganese, and Chromium 54
The Infra-Red Arc Spectrum of Iron 42
BATEMAN, H. Review of: *A Treatise on the Sun's Radiation and Other Solar Phenomena*, Frank H. Bigelow 355
CARTER, EDNA, and ARTHUR S. KING. A Further Study of Metallic Spectra Produced in High Vacua 224
DERSHEM, ELMER, and JOEL STEBBINS. Photo-Electric Measures of the Light of Nova Aquilae No. 3 344
ELLERMAN, FERDINAND, S. B. NICHOLSON, and A. H. JOY, GEORGE E. HALE. The Magnetic Polarity of Sun-Spots 153
FORSYTHE, W. E. Monochromatic and Neutral-Tint Screens in Optical Pyrometry 237
FROST, EDWIN B. A Star with Disappearing Bright Lines 61
Review of: *Science and Learning in France, with a Survey of Opportunities for American Students in French Universities: an Appreciation by American Scholars*, John H. Wigmore, *Editor-in-Chief* 63
GLANCY, A. ESTELLE. The Spectrum of Comet Mellish (1915*a*) . . . 196
HAGEN, J. G. Correlation between the Color-Scales of One and of Two Dimensions 282
HALE, GEORGE E., FERDINAND ELLERMAN, S. B. NICHOLSON, and A. H. JOY. The Magnetic Polarity of Sun-Spots 153
HASTINGS, C. S. Review of: *Mirrors, Prisms and Lenses*, James P. C. Southall 359
JOY, ALFRED H., and WALTER S. ADAMS. The Motions in Space of Some Stars of High Radial Velocity 179
The Orbits of Three Spectroscopic Binaries 186

PAGE

JOY, A. H., GEORGE E. HALE, FERDINAND ELLERMAN, S. B. NICHOLSON, and. The Magnetic Polarity of Sun-Spots 153

KING, ARTHUR S. Discussion of Some Evidence on the Origin of Radiation in the Tube-Resistance Furnace. 48

KING, ARTHUR S., and EDNA CARTER. A Further Study of Metallic Spectra Produced in High Vacua 224

KUNZ, JACOB, and JOEL STEBBINS. A Photo-Electric Determination of the Brightness of the Corona at the Eclipse of June 8, 1918. 137

LINDBLAD, BERTIL. On the Use of Grating Spectra for Determining Spectral Type and Absolute Magnitude of the Stars 289

LUCKIESH, M. Aerial Photometry 108

NICHOLSON, S. B., GEORGE E. HALE, FERDINAND ELLERMAN, and A. H. JOY. The Magnetic Polarity of Sun-Spots 153

PARKHURST, J. A. A Property of the Photographic Plate Analogous to the Purkinje Effect 202

Review of: *Geschichte und Literatur der veränderlichen Sterne.* Band I, G. Müller und E. Hartwig 286

PAULSON, J. E. Spectra and Atomic Numbers of the Elements . . 276

PLASKETT, J. S. The Stellar Spectrograph of the 72-Inch Reflecting Telescope 209

RANDALL, H. M., and E. F. BARKER. The Infra-Red Arc Spectra of Cobalt, Nickel, Manganese, and Chromium 54

The Infra-Red Arc Spectrum of Iron 42

SANFORD, FERNANDO. The Helium Spectrum and the Unit Electrical Charge 337

SHAPLEY, HARLOW. Studies Based on the Colors and Magnitudes in Stellar Clusters.

Ninth Paper: Three Notes on Cepheid Variation 24

Tenth Paper: A Critical Magnitude in the Sequence of Stellar Luminosities 96

Eleventh Paper: A Comparison of the Distances of Various Celestial Objects 249

Twelfth Paper: Remarks on the Arrangement of the Sidereal Universe 311

SHINOMIYA, T. Color-Sensitiveness of Photo-Electric Cells . . . 303

SLIPHER, V. M. On the General Auroral Illumination of the Sky and the Wave-Length of the Chief Aurora Line 266

SPARROW, C. M. Theory of Imperfect Gratings 65

STEBBINS, JOEL, and ELMER DERSHEM. Photo-Electric Measures of the Light of Nova Aquilae No. 3 344

STEBBINS, JOEL, and JACOB KUNZ. A Photo-Electric Determination of the Brightness of the Corona at the Eclipse of June 8, 1918 . . 137

VAN BIESBROECK, G. Review of: *The Binary Stars*, Robert Grant Aitken 131

Articles that will appear in forthcoming numbers of the *Astrophysical Journal*

On Progressive Changes of the Wave-Lengths of Lines in Stellar Spectra with Change of Type. By SEBASTIAN ALBRECHT.

The Physical Interpretation of Albedo, II: Saturn's Rings. By LOUIS BELL.

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